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Upper extremity rehabilitation using interactive virtual environments

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ABSTRACT

UPPER EXTREMITY REHABILITATION USING INTERACTIVE VIRTUAL ENVIRONMENTS

by
Qinyin Qiu

Stroke affects more than 700,000 people annually in the U.S. It is the leading cause of major disability. Recovery of upper extremity function remains particularly resistant to intervention, with 80% to 95% of persons demonstrating residual upper extremity impairments lasting beyond six months after the stroke. The NJIT Robot Assistive Virtual Rehabilitation (NJIT-RAVR) system has been developed to study optimal strategies for rehabilitation of arm and hand function. Several commercial available devices, such as HapticMaster™, Cyberglove™, trakSTAR™ and Cybergrasp™, have been integrated and 11 simulations were developed to allow users to interact with virtual environments. Visual interfaces used in these simulations were programmed either in Virtools or in C++ using the Open GL library. Stereoscopic glasses were used to enhance depth perception and to present movement targets to the subjects in a 3-dimensional stereo working space. Adaptive online and offline algorithms were developed that provided appropriate task difficulty to optimize the outcomes.

A pilot study was done on four stroke patients and two children with cerebral palsy to demonstrate the usability of this robot-assisted VR system. The RAVR system performed well without unexpected glitches during two weeks of training. No subjects experienced side effects such as dizziness, nausea or disorientation while interacting with the virtual environment. Each subject was able to finish the training, either with or without robotic adaptive assistance.

To investigate optimal therapeutic approaches, forty stroke subjects were randomly assigned to two groups: Hand and Arm training Together (HAT) and Hand and Arm training Separately (HAS). Each group was trained in similar virtual reality training environments for three hours a day, four days a week for two weeks. In addition, twelve stroke subjects participated as a control group. They received conventional rehabilitation training of similar intensity and duration as the HAS and HAT groups. Clinical outcome measurements included the Jebsen Test of Hand Function, the Wolf Motor Function Test, and the ReachGrasp test. Secondary outcome measurements were calculated from kinematic and kinetic data collected during training in real time at 100 Hz. Both HAS and HAT groups showed significant improvement in clinical and kinematic outcome measurements. Clinical improvement compared favorably to the randomized clinical trials reported in the literature. However, there was no significant improvement difference between the two groups. Subjects from the control group improved in clinical measurements and in the ReachGrasp test. Compared to the control group, the ReachGrasp test showed a larger increase in movement speed during reaching and in the efficiency of lifting an object from the table in the combined HAS and HAT group.

The NJIT-RAVR system was further modified to address the needs of children with hemiplegia due to Cerebral Palsy. Thirteen children with cerebral palsy participated in the total of nine sessions of one hour training that lasted for three weeks. Nine of the children were trained using the RAVR system alone, and another four had training with the combined Constraint-Induced Movement therapy and RAVR therapy. As a group, the children demonstrated improved performance across measurements of the Arm Range of Motion (AROM), motor function, kinematics and motor control. While subjects' responses to the games varied, they performed each simulation while maintaining attention sufficient to improve in both robotic task performance and in measures of motor function.

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USING INTERACTIVE VIRTUAL ENVIRONMENTS

by
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Selected peer-reviewed publications (in chronological order).

Most relevant to the current application

1. Merians AS, Fluet GG**, Qiu Q**, Saleh S, Lafond I, Davidow A, Adamovich SV.(2011), Robotically facilitated virtual rehabilitation of arm transport integrated with finger movement in persons with hemiparesis. Journal of NeuroEngineering and Rehabilitation. May, 16;8:27.
2. Fluet, G**., Qiu, Q**., Saleh, S., Ramirez, D.A., Kelly, D., Parikh, H.DAdamovich, S. (2010). Interfacing a haptic robotic system with complex virtual environments to treat impaired upper extremity motor function in children with cerebral palsy. Developmental Neurorehabilitation, 13(5):335-45.
3. **Qiu, Q.,** Ramirez, D.A., Saleh, S., Fluet, G., Parikh, H.D., Kelly, D., Adamovich, S. (2009) The New Jersey Institute of Technology Robot-Assisted Virtual Rehabilitation (NJIT-RAVR) system for children with cerebral palsy: A feasibility study, Journal of NeuroEngineering and Rehabilitation, 16, 6-40.
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9. **Qiu Q.,** Fluet G.G., Merians A.S., Mathai A. and Adamovich S. (2008) Design of Robotically Facilitated Simulations in Virtual Environments to Train the Hemiplegic Upper Extremity of Persons Post-Stroke. RESNA 2008 Annual Conference proceedings, June 26-30, 2008, Washington, DC
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11. **Qiu Q.,** Ramirez D.A., Swift K., Parikh H.D., Kelly D. and Adamovich S. (2008). Virtual Environment for Upper Extremity Rehabilitation in Children with Hemiparesis., 34th Annual Northeast Bioengineering Conference proceedings, pp. 203-204, April 3-6, 2008, Brown University, Providence, RI

献给

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CHAPTER 1

INTRODUCTION

1.1 Stroke

In America 700,000 people annually sustain a stroke (American Stroke Association). It is the leading cause of major disability. The percentage of stroke survivors with major disability is rising as the stroke survival rate increases. Deficits in motor control affect the stroke survivors' capacity for independent living and economic self-sufficiency. The impact of even mild to moderate deficits in hand control in particular, effect many activities of daily living.

Hand rehabilitation is a challenge perhaps for the following reasons. First is the complexity of the upper extremity function. The upper extremity is an interdependent system that requires the shoulder, elbow and hand to act in coordination with each other [1, 2]. The role of the upper extremity is constantly changing from primary mover, to stabilizer, to manipulator as one interacts with an object, and this change is based on the physical, spatial and temporal characteristics of a task [3-5]. Another possible cause of this challenge is competitive neuro-network plasticity [6]. Cortical expression of hand and arm are adjacent and overlap somewhat with each other in the brain. A mutually inhibitory relationship between proximal and distal upper extremity effectors in persons with stroke has been demonstrated experimentally [7]. Studies report that the repetitive practice of motor activities increases the area and density of cortical areas corresponding to the practiced movement [8-10]. This phenomenon of use dependent plasticity includes the sharing of overlapping cortical space with adjacent representations. Therefore, rehab training of arm prior to hand as traditional therapy might actually result in less cortical space for the hand to recover.

Although there are a great variety of interventions aimed at enhancing recovery in the weakened limbs, functional outcomes are inconsistent [11-13] and it is not clear whether these interventions actually improve recovery beyond inherent spontaneous resolution [14]. Because of fiscal constraints, current service delivery models favor gait-training and proximal arm function [15]. And the effectiveness of intervention strategies have generally been less pronounced for the upper extremity than for the lower extremity [15-18]. Therefore, investigation into upper extremity rehabilitation is an important topic in order to improve the potential outcome for survivors of stroke through recovery of skills of daily living.

1.2 Training-induced Neuroplasticity

Animal and human studies have shown that important variables in learning and relearning motor skills and in changing neural architecture are the quantity, duration and intensity of training sessions. There is evidence to demonstrate that plasticity is "use-dependent" and intensive massed and repeated practice may be necessary to modify neural organization [19-22] and affect recovery of functional motor skills [23-25]. The importance of intensity and repetition has also been confirmed for stroke patients in the chronic phase [26] specifically in the treatment paradigm referred to as constraint-induced-movement-therapy (CIMT). Use-dependent cortical expansion has been shown up to 6 months following 12-days of CI therapy in people post stroke [27]. In addition to the repetitive and intensive training necessary to induce neural plasticity, sensorimotor stimulation must involve the learning of new motor skills. Evidence suggests that learning new motor skills is essential for inducing functional plasticity [28-30]; therefore, it appears that critical variables necessary to promote motor changes and induce neural plasticity are the dynamic and adaptive development and formation of new motor skills. It is believed that adaptive training paradigms that continually and interactively move the motor outcome closer and closer to the targeted skill are important to foster formation of better organized motor skills [31].

1.3 Virtual Reality Based Neurorehabilitation

Dependence on existing therapies alone to promote neuroplastic changes might not always be practical. For example, changes at the synaptic level are evident in the rodent brain after the animal is exposed to thousands of repetitions of a given task over a short interval of time, i.e., 12,000 repetitions over 2-3 days [8, 28]. In stark contrast, the affected extremity of the human is moved at best 1-2 hours/day in the weeks after stroke [32] and as few as 10-20 repetitions per training session in the chronic phase [33]. More than 50% of the time spent on rehabilitation focuses on the lower extremities and balance rather than the hand [34-36]. Use of Virtual Reality (VR) as a training environment may provide a rehabilitation tool that can be used to exploit the nervous systems' capacity for sensorimotor adaptation by providing a technological method for individualized intensive, repetitive, and adaptive training. In addition to the training intensity and volume necessary to induce neural plasticity, sensorimotor stimulation must involve the learning of new motor skills. Computerized systems are well suited to this and afford great precision in automatically adapting target difficulty based on individual subject's ongoing performance. Virtual environments (VE) can be used to present complex multimodal sensory information to the user and have been used in military training, entertainment simulations, surgical training, spatial awareness training and more recently as a therapeutic intervention for phobias [37-40]. When virtual reality simulations are interfaced with movement tracking and sensing glove systems they provide an engaging, motivating and adaptable environment where the motion of the limb displayed in the virtual world is a replication of the motion produced in the real world by the subject.

Virtual reality systems are generally classified by the visual presentations they provide to a participant, the presence or absence of somatosensory feedback and the modality used to collect data from the participant. Visual stimuli are grouped by the level of immersion. Two-dimensional presentations are considered non-immersive. Three dimensional presentations utilizing stereoscopic projections or displays with a fixed visual perspective are considered semi-immersive. Fully immersive systems allow for changing visual perspective with head movement. There are a myriad of methods of collecting data from a subject. Some systems utilize joysticks, hand controls or steering wheels. Motion tracking systems that utilize video and optoelectronic cameras, electromagnetic and ultrasound sensors, accelerometers and gyroscopes provide kinematic data. Instrumented gloves can add precision to tracking of hand motion. The data collected from these devices is used to control a computerized representation of the user or an avatar that represents their movements and interacts with the VE. Video capture virtual reality (VCVR) is a family of video camera based motion capture systems that record and digitize pictures of participants as they move, and transfer those images into a virtual environment, in real time [41]. These systems differ from other forms of VR in terms of their visual presentation which is a mirror image of the participant. Flicker glasses that display alternating right/left views of the picture or head-mounted visual displays (HMD) may be used for an experience of greater immersion (for both gait and upper extremity systems). The most immersive system is the CAVE (University of Illinois at Chicago) which is a room-size, 3D video and auditory system. Finally, newer systems that utilize robots to provide interaction forces between the user and VE are classified as haptic systems. Several systems like GENTLE-S [42], MIT-Manus [3] and PneuWREX [43] can be used to provide haptic effects during upper extremity activities in VEs. Many disciplines of healthcare now rely on VR, such as for training surgeons [44], delivery of cognitive therapy [45], and delivery of post-traumatic stress disorder therapy [46]. The use of VR for sensorimotor training is a promising addition to its already broad utility in healthcare. Initial investigations into this family of approaches to rehabilitation emerged in the mid 1990's. Several reviews summarize the first generation of this research [41, 47-50], with more recent systematic reviews examining the clinical efficacy of sensorimotor training in VE for rehabilitating upper extremity function [51] and gait [52] after stroke.

The above sections provide an overview of the multifaceted components in skill reacquisition, such as mass practice, rich environments, system adaptability, and timing of VR delivery that may mediate neuroplasticity following a lesion. The versatility of VR in these respects offers the clinician various ways to modulate brain reorganization. However, perhaps an even more appealing aspect of VR is its versatility in presenting complex sensory stimulation, through a combination of visual, somatosensory (haptic), and auditory feedback. Intelligent manipulation of these parameters may offer the clinician a yet unattained level of control over the therapeutic impact of a given intervention. The current state of the art in using these approaches is reviewed below.

1.4 Virtual Reality Rehabilitation with Robot Assistance

One of the limitations of VR is the relatively high level of motor function required to interact with these systems [53]. One approach to broadening the group of people that can utilize VR and gaming technology for motor rehabilitation has been combining adaptive robotic systems that interface with virtual environments. Newer studies show that robotically-facilitated repetitive movement training might be an effective stimulus for normalizing upper extremity motor control in persons with moderate to severe impairments who have difficulty performing unassisted movements [54, 55].

Hogan and colleagues designed a suite of robots starting with the MIT-MANUS a 2 DOF robot that trained the shoulder and elbow in a horizontal plane [55]. Subsequent additions to their suite include a 1 DOF robot that can train shoulder movements in vertical or diagonal planes [56], and a third that trains the wrist in three DOF [57]. Participants interact with the end effector of these robots at the hand and their arms are supported by external structures. Trajectories of the participant may be shaped utilizing a haptic channel that limits negative trajectories and movement that deviates from a predetermined positive trajectory [58]. The PARIS system was designed to work in larger three dimensional workspaces and to either train or study the effects of adjusting actual task parameters and distortion of tasks or feedback and their effect on motor learning and control [59]. The NeReBot and the MariBot are two wire based robot systems designed to provide passive range of motion treatments to the shoulder and arm of patients with minimal active movement [60].

Exoskeleton robots provide an alternative to end effector robots in their ability to control individual joint torques and velocities. The ARMin system facilitates a patient interacting in virtual environments utilizing a principle described as minimal intervention [61]. The impedance controlled robot provides assistance only when the subject moves outside predetermined trajectories or a range of joint torques. The PneuWREX is a four DOF, pneumatically actuated exoskeleton with a grip sensor that allows subjects to train the hand and arm as a functional unit in a series of complex virtual environments [54]. The RUPERT system [62] is a portable, wearable, exoskeleton robot that facilitates movement of the arm and shoulder and can facilitate interactions with real world objects.

Van der Linde et al. describes the HapticMaster™, an admittance controlled haptic robot that senses forces applied by the subject and controls motion of the subjects arms in response the applied forces. It is well suited for virtual environment interface and neurorehabilitation [63, 64]. Several robotic rehabilitation systems have been designed using the Haptic Master. Harwin et al. designed the GENTLE/S a system in which participants perform upper extremity movements using the Haptic Master, in a series of virtual environments that follow a continuum of visual complexity [65]. The robot augments the participant's movement with a haptic spring and damper system that maintains a trajectory and velocity determined by the participant's therapist. The spring and damper system control is modeled using the "bead" concept [66]. The Am Coordination Training 3D Device utilizes the Haptic Master to study the kinematics of three dimensional reaching activities by persons with upper extremity hemiparesis in virtual space [67].

However, most of these robotic devices are designed for only shoulder and elbow motion and not for fine-motor hand activities. Many of these systems either employ the robot as a passive assisting device, or they use the robot to apply external force to shape the arm movement pattern. Many of these systems focus primarily on unilateral activities (one arm only), and emphasize upper arm therapy only. One important caution in this approach is that constant force assist will depress voluntarily control, which will decrease the therapeutic effects [68]. Another is that training that employs static training algorithms and systems that focus only on the upper arm might alter desired rehabilitation outcome.

This document will focus upon design, development, testing, and rehabilitation experiences employing NJIT Robot Assisted Virtual Reality (RAVR) system which uses a unique therapy approach and custom robot assisted VR system. This therapy approach and custom robot assisted VR system can adaptively train hand and arm together as one unit. Adaptive algorithms that are used in the system dynamically control the robot assistance level to encourage voluntary movement as much as possible which might increase the therapeutic effects.

CHAPTER 2

NJIT ROBOT ASSISTED VIRTUAL REALITY (RAVR) SYSTEM DESIGN

The NJIT Robot Assistive Virtual Reality (NJIT-RAVR) system has been designed and developed for upper extremity rehabilitation for patients who have experienced cerebrovascular accidents. Author's approach was to combine several commercially available devices which have been integrated into the system; eleven simulations were designed and developed to allow users to interact with virtual environments. The systems utilize a variety of models and technologies to facilitate and augment upper extremity movement for persons with hemiparesis. One common aspect to the majority of existing systems is that trajectories, velocities, and assistance levels are predetermined and maintained throughout the movement. Author's approach described differs in that it utilizes the Haptic Master's ability to measure forces, velocity and position in real time, allowing it to utilize on-line algorithms to adjust haptic effects such as assistance against gravity, assistance in the direction of the target, and damping [69]. In author's design and implementation, these adjustments can be applied during the movement to enable the subject to accomplish the motor task with minimal external support. In addition, the level of assistance in the system can be varied from trial to trial depending on the subject's performance throughout a session, with the goal of maximizing the participant's output while maintaining a reasonable success-rate. Finally, the Haptic Master as a newer generation, admittance controlled robot combines the ability to render minimal friction with the capacity to create very rigid constraints that can be used to present haptic objects in virtual environments for the indirect shaping of arm movement trajectories.

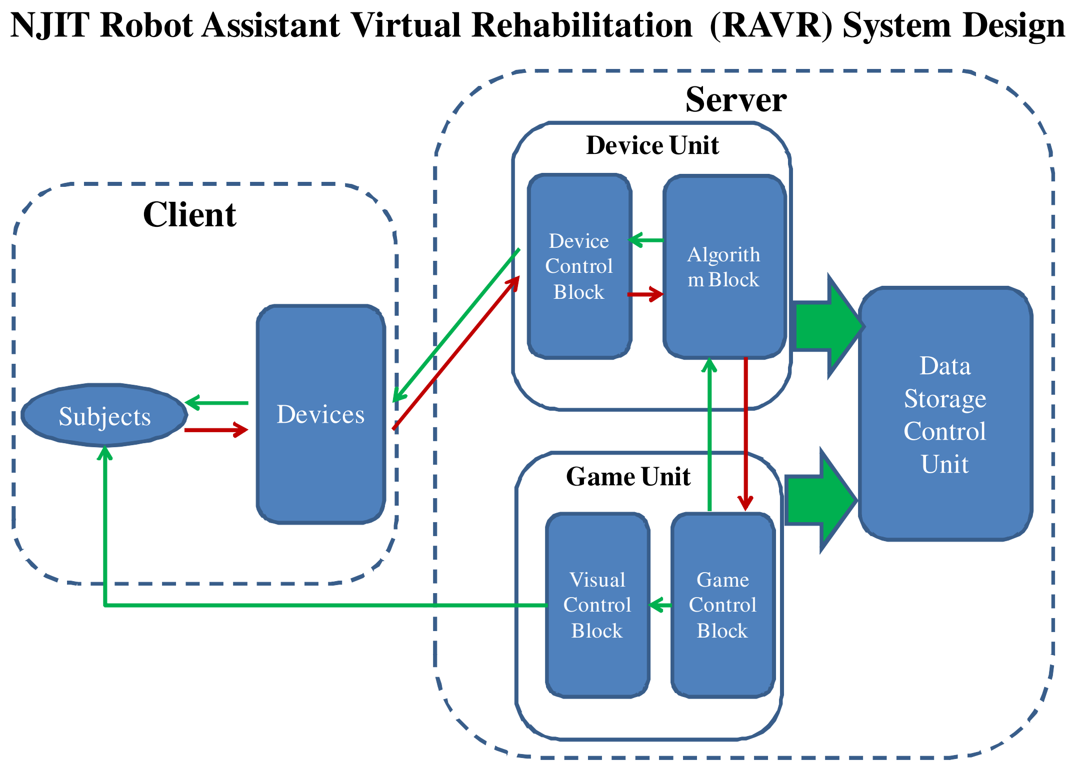


Figure 2.1 NJIT RAVR system has two main components: client side and server side. Client side includes robot and other hardware devices for hand and arm interacted with subjects. Server side includes device unit, game control unit and data storage control unit.

NJIT RAVR system has two main components: client side and server side (Figure 2.2). Client side includes robot and other hardware devices for hand and arm interacted with subjects. Server side includes device unit, game control unit and data storage control unit. Signal from devices controlled by subjects was sent to device control block in server side. Device control block sorts signal into different categories such as force, velocity and position. Sorted signal is sent to algorithm block to adjust assistant force and game difficulty level. Algorithm block also communicates with Game Control block to see if there is any game check point has been reached. For example, if correct finger was flexed on correct key, or if the game had reached the end. After that, signal will be adjusted accordingly and send back to devices through device control block to move device appropriately. At the same time, visual feedback was sent to subject through visual feedback block as well. Data collected from devices and game variables from game unit were sent to data storage block for offline analysis.

2.1 System Hardware

2.1.1 Hand

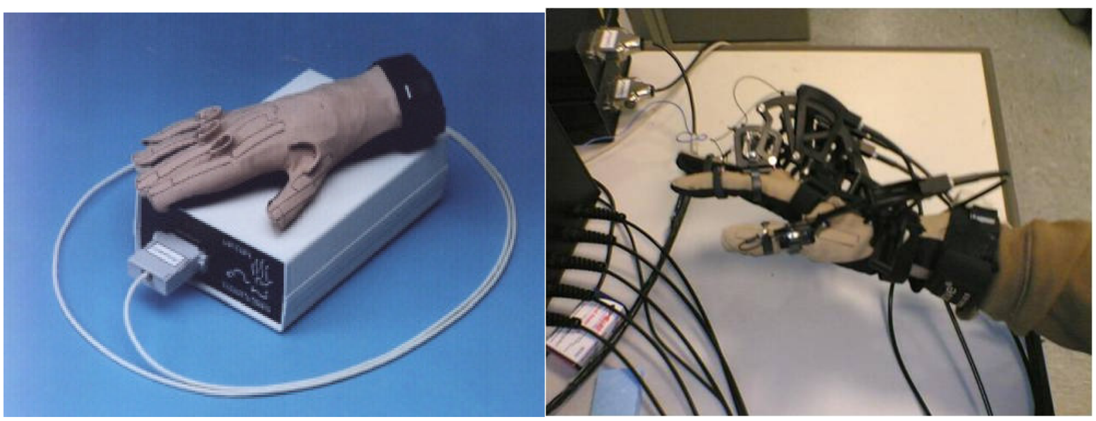


Figure 2.2 Left: CyberGlov™. Right: CyberGrasp™ fits on the top of the CyberGlove™.

The NJIT RAVR system supports the use of CyberGlove™ [70] instrumented gloves for measuring finger joint angles and a CyberGrasp™ hand exoskeleton [70] for haptic effects. The CyberGrasp™ device is a lightweight, force reflecting exoskeleton that fits over a CyberGlove™ data glove and adds resistive force feedback to each finger. The CyberGrasp™ is used in the system to facilitate individual finger movement by resisting flexion of the adjacent fingers in patients with mass grasp deficits thus allowing for isolated movement of each finger. The trakSTAR™ [70] is used for tracking hand position and orientation. Finger displacement, hand position and orientation are recorded in real time and translated into three dimensional movements of the virtual hands shown on the screen in a first-person perspective .

2.1.2 Arm

The NJIT RAVR system's arm simulations utilize the Haptic MASTER (Moog NCS, The Netherlands), a three degrees of freedom admittance controlled (force controlled) robot. Three more degrees of freedom (yaw, pitch and roll) can be added to the arm by using a gimbal, with force feedback available only for pronation/supination (roll). A three-dimensional force sensor measures the external force exerted by the user on the robot. In addition, the velocity and position of the robot's endpoint are measured. These variables are used in real time to generate reactive motion based on the properties of the virtual haptic environment in the vicinity of the current location of the robot's endpoint. This allows the robotic arm to act as an interface between the participants and the virtual

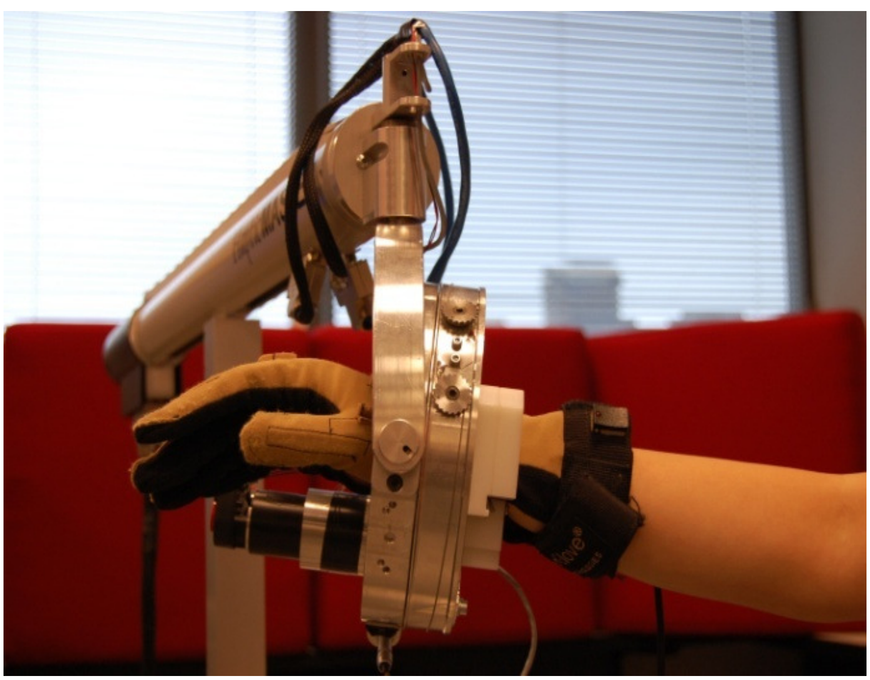


Figure 2.3 HapticMaster™ with ring gimbal support and CyberGlove.

environments enabling multiplanar movements against gravity in a 3D workspace. The haptic interface provides the user with a realistic haptic sensation that closely simulates the weight and force found in upper extremity tasks.

For the NJIT RAVR system, forearm- and hand-based volar splints of various sizes were fabricated to connect the subject's impaired hand to the ring gimbal. Splints were chosen for each subject in order to allow for the highest degree of freedom of movement while minimizing abnormal movement patterns.

2.2 Software

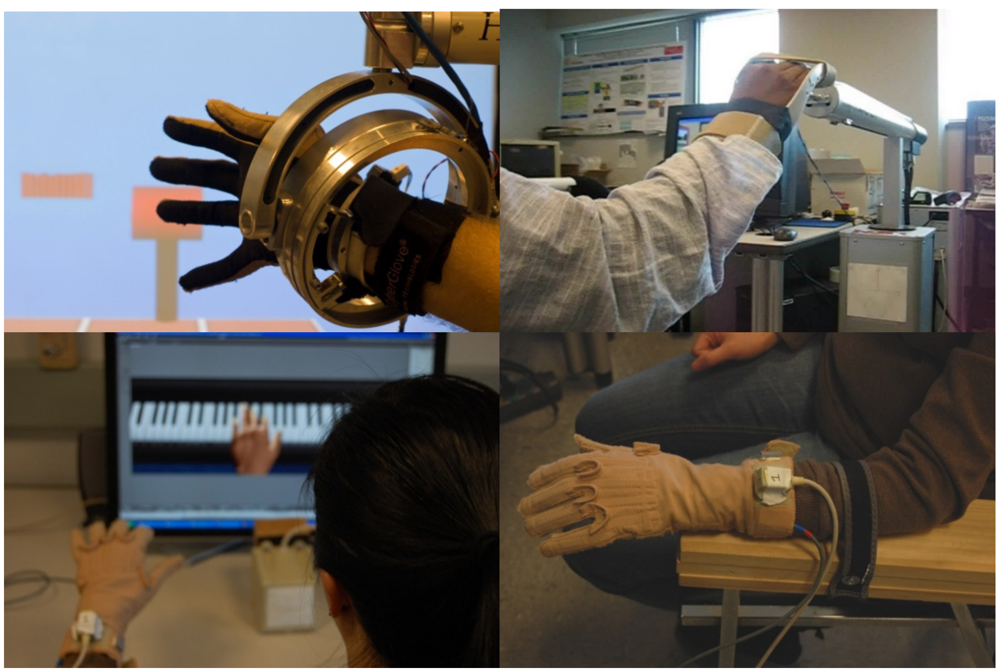


Figure 2.4 Upper and lower left panels show the HAT mode when patient's impaired arm is attached to the robot or position tracker with CyberGlove on the hand. Upper and lower right panels show the HAS mode when either patient's impaired arm is attached to the robot or patient wears a CyberGlove with arm fixed at one position.

NJIT RAVR system includes two modes, integrated (Hand and Arm together, HAT) and isolated (Hand and Arm separated, HAS). As shown in Figure 2.4, upper and lower left

Table 2.1 Task-Based Simulations

Simulation+Effector(s) Used	Children/Adult	Hardware	Motion Trained
Hand			
Piano Trainer 1	A	C/ F	Finger individuation
Space Pong	A	C/F	Finger flexion/extension
Upper Arm + Elbow			
Placing Cups	C/A	R	Shoulder flexion/extension Elbow flexion/extension
Reach-Touch Bubble Explosion**	C/A	R	Shoulder flexion/extension Elbow flexion/extension
Falling Objects	C	R/F	Shoulder flexion/extension Shoulder abduction/adduction
Space Ship	A	R	Shoulder flexion/extension Elbow flexion/extension
Upper Arm + Forearm			
Hammer 1	C/A	R/G	Shoulder flexion/extension Elbow flexion/extension Forearm supination/pronation
Race Cars	C	R/G	Shoulder flexion/extension Elbow flexion/extension Forearm supination/pronation
Upper Arm + Hand			
Piano Trainer 2	A	C/ F	Finger individuation Shoulder abduction/adduction
Plasma Pong	A	C/ F	Shoulder flexion/extension Finger extension
Humming Bird Hunt	A	C/ F	Shoulder flexion/extension Shoulder abduction/adduction Pincer Grasp
Hammer 2	A	R/C/ F	Shoulder flexion/extension Elbow flexion/extension Finger flexion/extension

Hardware required*: R is robot, F is Flock of Birds, G is CyberGlove

panels illustrate the HAT mode when patient's impaired arm is attached to the robot or position tracker with CyberGlove™ on the hand. Simulations for HAT require patients to exercise shoulder, elbow and hand simultaneously. Upper and lower right panels illustrate the HAS mode when either patient's impaired arm is attached to the robot to exercise should and elbow only, or patient is wearing a CyberGlove™ with arm fixed at one position to exercise fingers only. Each mode has its own set of simulations. Total of 11 simulations have been developed as listed in Table 2.1. Table 2.1 also lists the appropriate patient population and hardware requirement for each simulation. The visual interfaces used in all simulations in this system were programmed either in C++ using the Open GL library or Virtools (Dassault Systemes, France). Stereoscopic glasses were used to enhance depth perception and present movement targets to the subjects in a three-dimensional stereo working space. CrystalEyes stereoscopic glasses (CrystalEyes, USA) were used to present the three dimensional visual environments. This process employs two graphic buffers, one for the left eye, another one for the right eye. CrystalEyes Stereoscopic glasses block one eye at a time with the same frequency as the computer refresh rate. This synchronization allows the right eye to see the right graphic buffer, and the left eye to see the left graphic buffer, which results in a three-dimensional stereo effect.

2.2.1 Simulation: Reach-Touch

The Reach Touch simulation was the first complex, customized, three-dimensional adaptive simulation designed and developed for the NJIT RAVR system. In the Reach-Touch simulation, the participant moves a virtual sphere in a three dimensional space in order to touch a series of ten haptically rendered targets (Figure 2.5a). This unique system and application design diagrams are shown in Appendix A, while examples of the code developed for rendering this system are shown in Appendix B. In this simulation, after reaching a target, the subject had to bring the cursor back to the starting position defined by a haptically rendered torus at the bottom of the screen. As soon as the cursor sphere is placed within the torus, the next target to be touched begins to flash. The goal of the task is to improve the speed and accuracy of a wide variety of shoulder and elbow movements within the context of aiming /reaching type movements performed in a functional

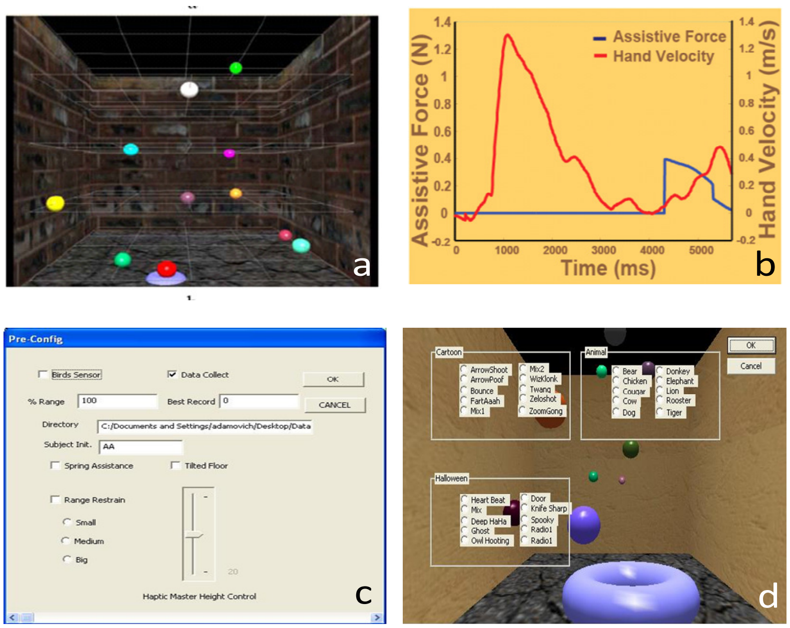


Figure 2.5 a. Screen shot of ReachTouch simulation. b. Online adjustment of the assistance force based on hand velocity. c. A pre-configured window allows the trainers to set up parameters before the training for each individual. d. options for selection of different sound effects to attract children's attention during training.

workspace. The working space of the Haptic Master can be calibrated for each subject to easily accommodate a wide variety of subject heights and available active range of motion.

Three haptic effects have been developed for this simulation to accommodate patients with varying degrees of impairment. One assistance mode provides an adjustable haptic spring that draws the subject toward the target. The amount of assistive forces (spring stiffness), starts at zero and gradually increases in 5 N/m increments every 10 milliseconds when the hand velocity or active force towards the target applied by the subject to the robot does not exceed predefined thresholds within 5 seconds after movement onset (Figure 2.5b). Current values of active force and hand velocity are compared online with threshold values. If either is above the threshold, the spring

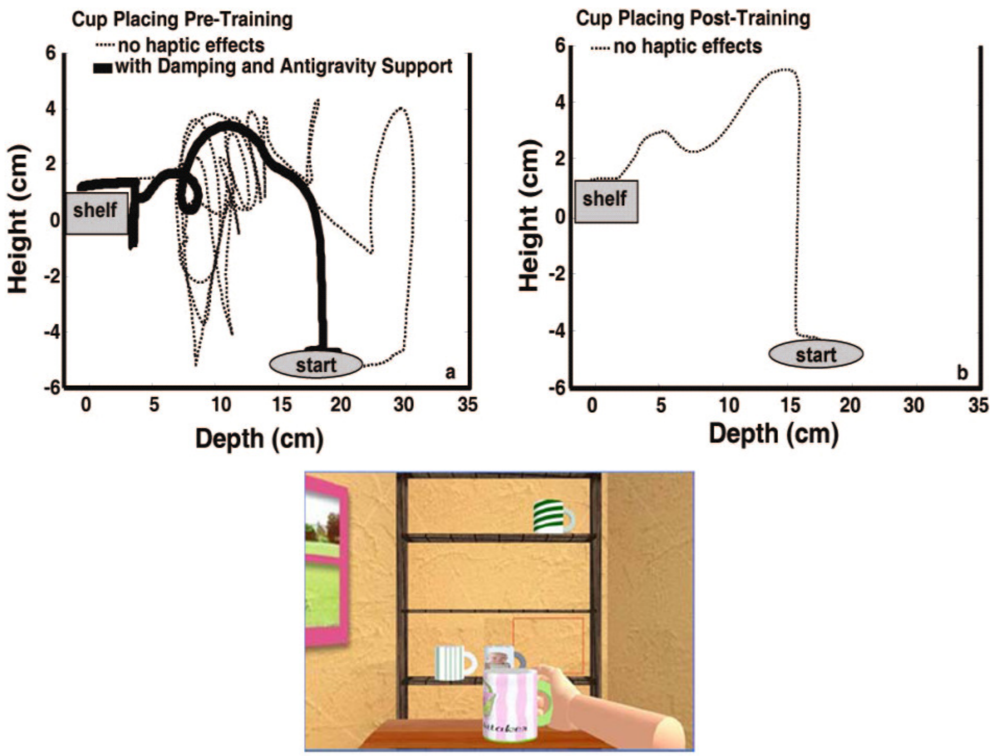


Figure 2.6 Upper left panel. Hand trajectory (side view) of Cups simulation with (bold line) and without (thin line) assistive haptic effects during the first day of training. Upper right panel. Hand trajectory of Cups simulation without haptic effects during the last day of training. Lower left panel shows a screen shot of the simulation.

stiffness starts to decrease in 5 N/m increments every 10 milliseconds. The range of the spring stiffness is from 0 to 10000 N/m. The velocity threshold is predefined according to the mean velocity of movement recorded from a group of neurologically healthy subjects and varies among the ten target spheres.

A second haptic effect, an invisible virtual ramp was designed to allow subjects with force generation impairments to perform three dimensional reaching movements against gravity. The ramp runs through the starting position and the target. Friction between the ramp and cursor is negligible. Support from the ramp through the Haptic Master decreases as percentage of the gravity force the participant overcomes, based on the angle formed by the ramp and the ground. As a result, the force necessary to move the upper extremity against gravity, toward the target is reduced. The ramp also decreases arm instability making this movement less tiring and frustrating for more impaired subjects.

A third haptic effect, an invisible range restriction, limits the participant's ability to deviate from an ideal trajectory toward each target, thus shaping the trajectories. All of the haptic effects can be modified to provide less assistance as the participants improve.

A pre-configured window (Figure 2.5c) that appears at the beginning of the trial allows engineers or therapists to customize training parameters for each individual such as the type of assistance, size of the working space, etc. In order to keep trainees' attention as long as possible, a pool of sound effects was implemented to allow trainees to generate different sound when popping up the bubbles. Children can choose from different animal sounds, cartoon sounds or scary Halloween sounds to replace the default explosion sound (Figure 2.5d).

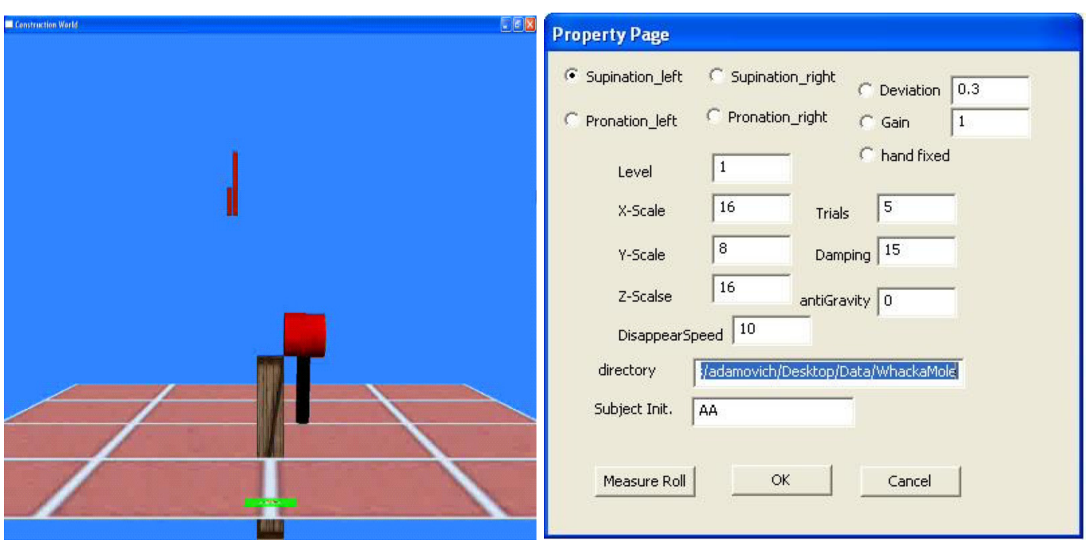


Figure 2.7 Left: screen shot of Hammer simulation. Right: a user friendly graphic interface to set up Hammer simulation training variables.

2.2.2 Simulation: Cups

The goal of the next simulation, Cup Placing, is to improve active range of motion and reaching accuracy. The screen displays a three-dimensional room with haptically rendered shelves and table. The participant uses their virtual hand (controlled by the hemiparetic arm) to lift virtual cups and place them onto one of the nine spots on the virtual shelves with three height levels shown in Lower left panel in Figure 2.6. Hand movement and viewpoint movement within the virtual environment are synchronized to maintain a clear view of the virtual hand throughout the activity in order to maintain focus on the task and increase the sense of involvement in the activity. A small target of a different color than the virtual hand denotes the area of the hand used to grasp the cup handle and a rectangular target indicates the correct placement of the cup on the shelf. The size of the targets can be reduced as the subject improves.

Dimensions of the cup placing task are calibrated to the subject's active range of motion and can be modified to be consistent with individual therapeutic goals. Calibration measures a subject's maximum reach 1) up and to the left, 2) up and to the right 3) down and to the left, and 4) down and to the right. The width of the shelves equals to 80% of the shortest excursion to the left or to the right that these movements elicited. The lowest and highest shelves are set at 80% of the lowest and highest excursions and the distance the shelves are set from the subject is 80% of the shortest horizontal excursion accomplished during the test. The calibration protocol itself can be used as an outcome measure. Haptic feedback is employed in this simulation. After the subjects acclimate themselves to the virtual environment, collisions with the table, shelves and other cups provide for normal feedback and feed-forward processes thus assisting in shaping the subjects' arm trajectories. The "weight "of the haptic cups can be adjusted, which allows for weighted strengthening activities for less impaired subjects as well as anti-gravity assisted movement for weaker subjects. An optional damping effect can be applied by the Haptic Master, which stabilizes the subject's movement trajectory in three dimensions. The augmented force feedback provided by the damping effect reduces the need for the user to grade forces compared to the freely moving Haptic Master (Figure 2.6). Again, these effects may be modified during training depending upon the subjects' performance. The goal of the haptic effects described in this simulation is to allow the subject to train reaching movements with minimal external support or guidance by manipulating spatial task parameters, force requirements, and utilizing haptically rendered obstacles.

2.2.3 Simulation: Hammer

The Hammer Task trains a combination of three dimensional reaching and of two different repetitive distal movements. Targets are presented in a scalable 3D workspace (Figure 2.7a). There are two versions of this simulation. One game exercises movement of the hand and arm together by having the subjects reach towards a wooden cylinder and then use their hand (finger extension or flexion) to hammer the cylinders into the floor. The other uses supination and pronation to hammer the wooden cylinders into a wall. The haptic effects allow the subject to feel the collision between the hammer and target cylinders as they are pushed through the floor or wall. Hammering sounds accompany collisions as well. The subjects receive feedback regarding their time to complete the series of hammering tasks.

A user friendly GUI interface (Figure 2.7b) is presented to the trainee at the beginning of the simulation to adjust the size of the cylinders, the amount of anti-gravity assistance provided by the robot to the arm and the time required to successfully complete the series of cylinders. In order to adaptively modify the task requirements and game difficulty, gain algorithm was implemented to reinforce the wrist rotation/ fingers extension in real time. If subject is able to finish cylinder before it disappears, gain will decrease thus requiring a bigger range of wrist rotation/ finger extension as shown in Figure 2.8.

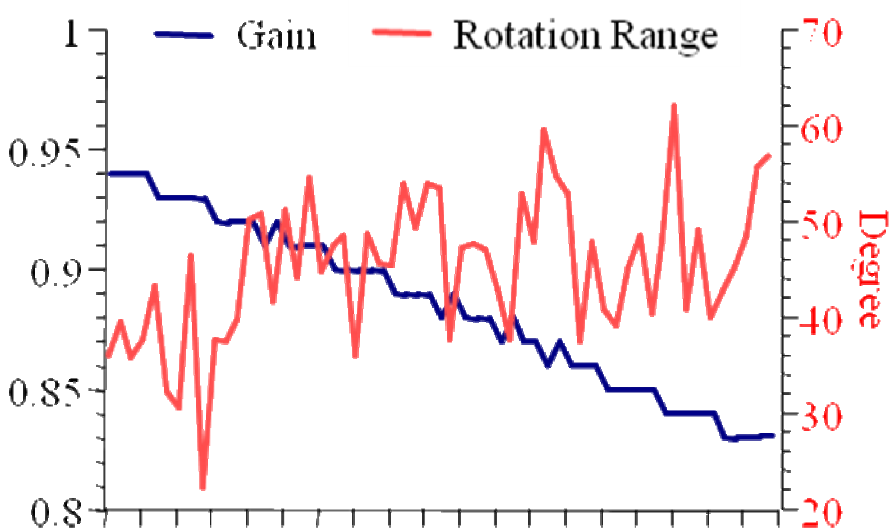


Figure 2.8 Wrist rotation range increases as gain decreases. This is an example from S19, day 3.

2.2.4 Simulation: Blood Cell

The Blood Cell simulation focuses on improving the speed & accuracy of frontal plane shoulder & elbow movements. The user moves a virtual space-ship through an environment representing the interior of a human blood vessel (Figure 2.9). Objects within the blood vessel represent obstacles and two different targets. A dual cognitive/motor task is required to perform the game successfully. Game speed, global

Figure 2.9 Screen shot of Blood Cell simulation.

forces, work space, and target/obstacle density can be adjusted to accommodate sensory and cognitive processing. Targets can be concentrated in quadrants to emphasize movement in a specific area of their reachable space. Feedback regarding their success is presented using scores.

2.2.5 Simulation: Virtual Piano Trainer

The piano trainer is a refinement and elaboration of one of the previous simulations [71] and is designed to help improve the ability of subjects to individually move each finger in isolation (fractionation). It consists of a complete virtual piano that plays the appropriate notes as they are pressed by the virtual fingers (Figure 2.10 a,b,c). The position and orientation of both hands as well as the flexion and abduction of the fingers are recorded in real time and translated into 3D movement of the virtual hands, shown on the screen in a first person perspective. The simulation can be utilized for training the hand alone to improve individuated finger movement (fractionation), or the hand and the arm together to improve the arm trajectory as along with finger motion. This is achieved by manipulating the octaves on which the songs are played. These tasks can be done unilaterally or bilaterally. The subjects play short recognizable songs, scales, and random notes. Color-coding between the virtual fingers and piano keys serve as cues as to which notes are to be played. The activity can be made more challenging by changing the fractionation angles required for successful key pressing (see Kinematic Measures Derived from VR System below). When playing the songs bilaterally, the notes are key-matched. When playing the scales and the random notes bilaterally, the fingers of both hands are either key matched or finger matched. Knowledge of results and knowledge of performance is provided with visual and auditory feedback.

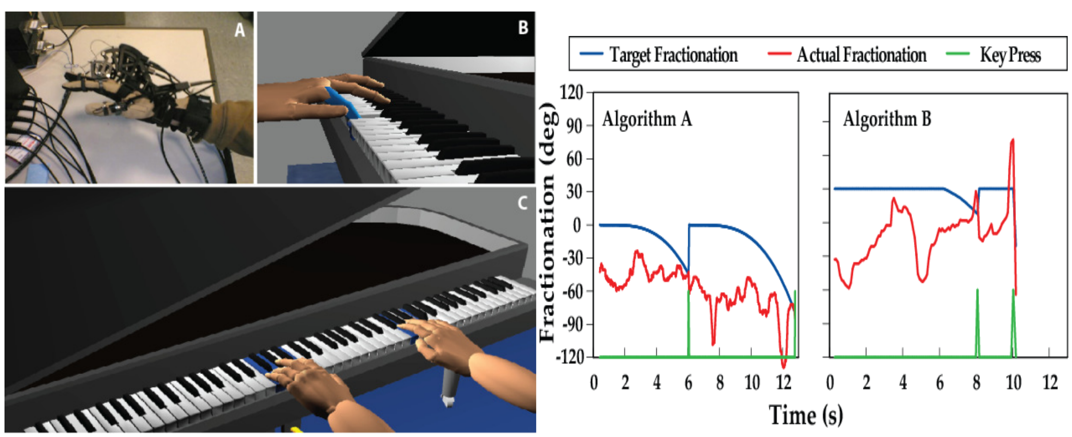


Figure 2.10 The CyberGrasp, a force reflecting exoskeleton robot inhibits mass grasp by maintaining inactive finger extension. b. Side view of a successful key press. c. Virtual Piano Trainer. d. Two different adaptive algorithms based on the amount of independent finger flexion (see text).

Peak fractionation score quantifies the ability to isolate each finger's motion and is calculated online by subtracting the mean of the MCP and PIP joint angles of the most flexed non-active finger from the mean angle of the active finger. When the actual fractionation score becomes greater than the target score during the trial, a successful key press will take place (assuming the subject's active finger was over the correct piano key). The target fractionation score starts at 0 at the beginning of each finger. After each trial, and for each finger, the algorithm averages the fractionation achieved when the piano key is pressed. If the average fractionation score is greater than 90% of the target, the target fractionation will increase by 0.005 radians. If the average fractionation is less than 75% of the target, the target will decrease by the same amount. Otherwise, the target will remain the same. There is a separate target for each finger and for each hand, (total

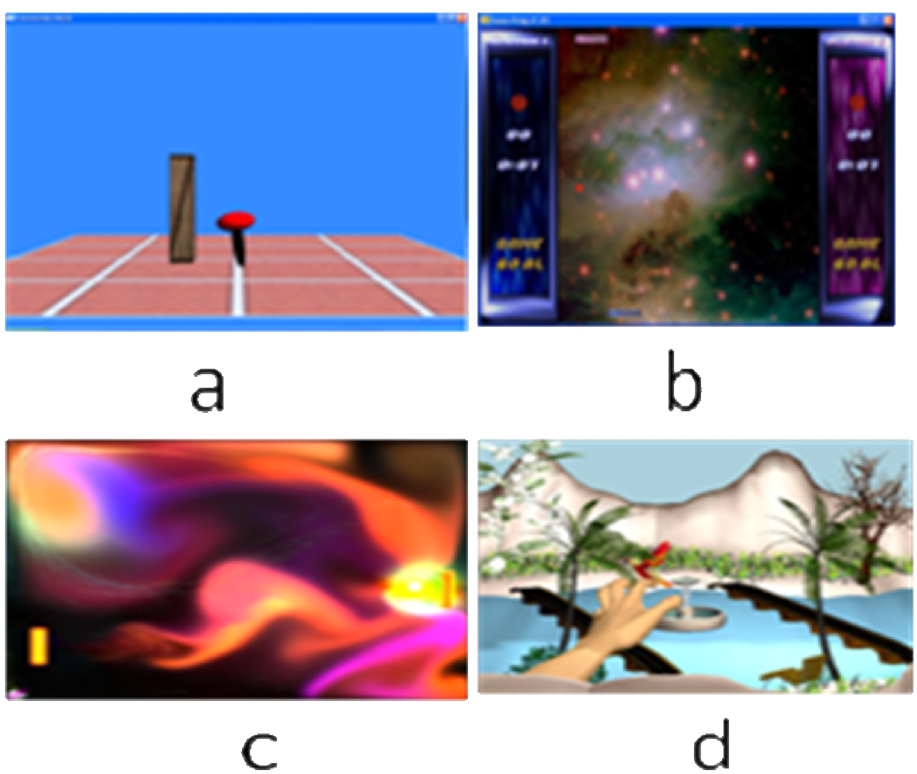


Figure 2.11 a. Hammer. b. SpacePong. c. Plasma Pong. d. HummingBird Hunt.

10 targets). Once a key is displayed for the subject to press, the initial threshold will be the set target. This will decrease during the trial according to the Bezier Progression (interpolation according to a Bezier curve) as shown in Figure 2.9 right panel. Thresholds will start at the target value and decrease to 0 or to a predefined negative number over the course of one minute. Negative limits for the target score will be used to allow more involved subjects to play the game.

2.2.6 Simulation: Space Pong

This activity was adapted from a free online game. The original game was played using mouse movement. A script was written to replace mouse movement with trackSTAR. There are two ways to play Space Pong simulation. One is to exercise hand movement by moving the pong paddle left and right using fingers flexion and extension. Another is to exercise radial and ulna deviation to control the pong paddle. Range of movement and speed of the target are adjustable at the beginning of the simulation base on subject impairment level (Figure 2.11b).

2.2.7 Simulation: Plasma Pong

This game was adapted from an existing game developed by Steve Taylor. The Pong paddle is moved with shoulder flexion and the target is engaged with finger extension, requiring the integration of shoulder flexion and finger extension (Figure 2.11c). The trajectories and speed of the target are unpredictable, necessitating constant conscious attention and feed-forward processing

2.2.8 Simulation: Hummingbird Hunt

This simulation depicts a hummingbird as it moves through an environment filled with trees, flowers and a river. Water and bird sounds provide a pleasant encouraging environment in which to practice repeated arm and hand movements (Figure 2.11d). The game provides practice in the integration of reach, hand-shaping and grasps using a pincer grip to catch and release the bird while it is perched on different objects located at different levels and in different sections of the workspace. The flight path of the bird is programmed into three different levels, low, medium and high allowing for progression in the range of motion required to successfully transport the arm to catch the bird. Adjusting the target position and/or size scales the difficulty of the task and the precision required for a successful grasp and release.

CHAPTER 3

FEASIBILITY STUDIES

3.1 Feasibility Study with Stroke Patients

3.1.1 Methods

Subjects were selected for the study based on the ability to actively extend the wrist of the hemiparetic limb at least 20° and extend the metacarpophalangeal (MCP) joints at least 10° which would fulfill or exceed the motor requirements necessary to participate in the lower functioning group of the EXCITE trial [72]. Subjects ranged from level five to level seven on the Chedoke McMaster Stroke Arm Impairment Inventory, a seven point ordinal scale with one corresponding to no active or reflexive movement and seven corresponding to rapid isolated against gravity movement. The group ranged from three to six on the Chedoke McMaster Stroke Hand Impairment Inventory which is scored similarly [73]. Two subjects demonstrated no upper extremity spasticity and the other two, mild to moderate spasticity as measured by a Physical Therapist using the Modified Ashworth Scale [74]. All patients were ambulatory without assistive devices and each

Table 3.1 Stroke Subjects Description in Feasibility Study

Subject	Age	Years Post CVA	HUE	DUE	CA	CH	SEA	EFA
S1	44	8	R	R	5	3	1/4	2/4
S2	72	4	R	R	6	6	0/4	0/4
S3	44	1	R	R	6	4	1+/4	1/4
S4	54	2	L	R	7	4	0/4	0/4

HUE = Hemiplegic UE, DUE = Dominant UE, CA = Chedoke Arm, CH = Chedoke Hand, SEA = Shoulder Extensor Ashworth, EFA = Elbow Flexor Ashworth had intact light touch on the dorsum of their impaired hand. None of the subjects demonstrated behaviors consistent with hemi-sensory inattention or neglect as observed by an experienced physical therapist but these constructs were not tested formally. All of the subjects reported normal or corrected normal visual acuity and no field cuts on their intake history. Table 3.1 shows clinical and demographic data for the subjects. Subjects 1 and 2 trained 3 hours per week for three weeks and two subjects (3 and 4) trained 4 hours per week for two weeks. Subjects were seated perpendicular to the Haptic Master with the robot in its neutral position and the interface knob 5 inches from the midpoint of their clavicle. Combinations of shoulder flexion, elbow extension, and horizontal adduction and abduction motions were trained. They performed 100 repetitions of the Reach-Touch simulation, 99 repetitions of the Cup Placing simulation and 50 repetitions of the Falling Object simulation. This training took about 90 minutes to 105 minutes at the beginning of the training period but as the subjects improved they were able to complete the same number of repetitions in 75 minutes. No adverse events or reactions occurred and there were no complaints consistent with cyber sickness, such as dizziness, nausea or disorientation [47], despite the fact that one of the activities (Reach-Touch) used partially immersive graphics.

3.1.2 Preliminary Results

During the testing activities, kinematic and force data were collected using unassisted conditions for the unimanual simulations. For the bilateral simulation, testing was performed in the presence of the assistive algorithm, and the amount of active force applied by the subject in the direction of the target was used as a test variable. These data as well as pre and post-test results for the Wolf Motor Function Test of Upper Extremity

Function were analyzed to compare the results of robotically collected kinematic and performance data and behavioral tests of upper extremity function. The small sample size and lack of control did not allow for testing to establish the efficacy of the system.

Figure 3.1c shows the percent change in the duration, and the smoothness of the trajectory used in the Reach-Touch simulation. All four subjects showed improvements in duration of the movement (31%, 35%, 44% and 35%), while three of the four subjects,

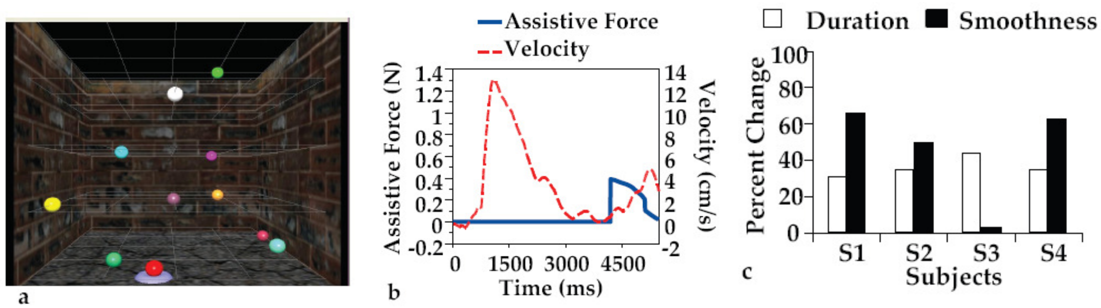


Figure 3.1 a. Visual presentation of the Reach-Touch simulation. b. Velocity / Assistive Spring Force changes during one trial of Reach-Touch. Four seconds after velocity toward the target approaches zero, the assistive force is initiated. The endpoint velocity toward the target then increases until the repetition is completed. c. Percentage improvement in kinematic measures following arm training using the Haptic Master during the three dimensional Reach-Touch simulation.

demonstrated improvement in the smoothness of the trajectory by 66%, 50% and 63%.

Figure 3.2b shows the percent changes for the same three measures for the Cup Placing simulation for each of the four subjects. All the subjects showed a decrease in the time needed to complete the task; the percent change in duration was 57%, 49%, 36%, and 26%. The improvement in the smoothness of the trajectories in all four subjects (91%, 84%, 32%, and 72%) suggests more neurologically integrated movements [75]. Figure 3.2c and d shows the hand trajectories generated by a representative subject in the Placing Cup activity pre and post training. In this simulation, the shelf and the table are haptically rendered as solid objects, so that the moving cup cannot cross their surface.

Figure 3.2c depicts a side view of a trajectory generated on day 1 of training, without haptic assistance, and another trajectory generated with additional damping and partial antigravity support. At the beginning of the training the subject needed the addition of the haptic effects to stabilize the movement and to provide enough arm support for reaching the virtual shelf. Because the shelf is haptically rendered it teaches the subject to produce

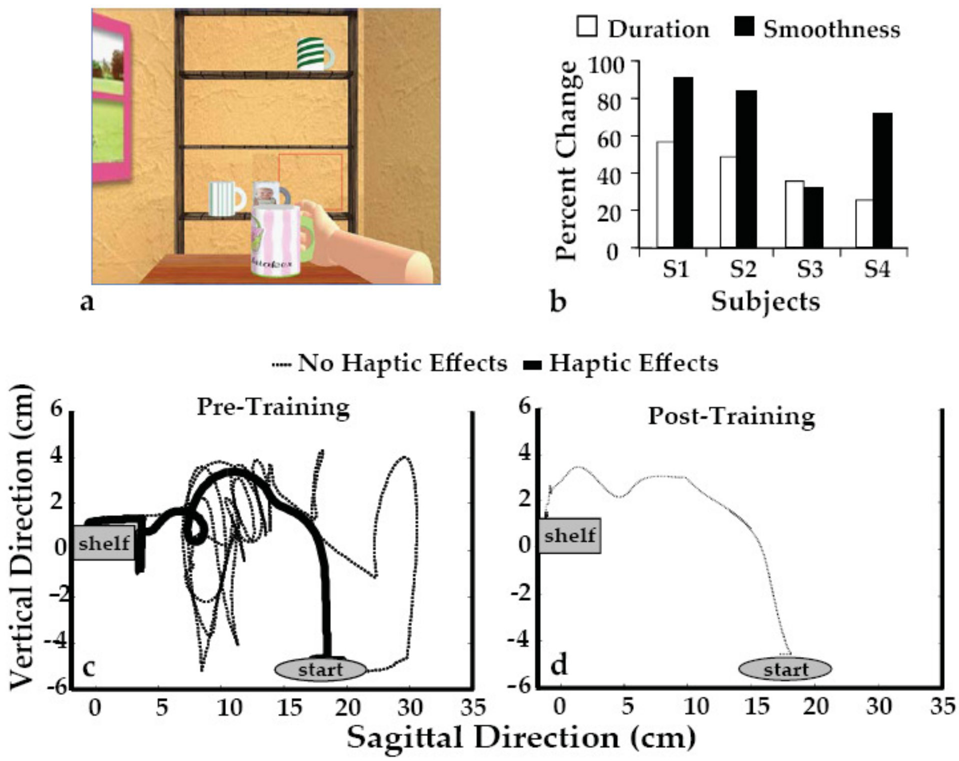


Figure 3.2 a. Visual presentation of the Cup Placing simulation. b. Percentage change in kinematic measures following arm training using the Haptic Master during the Cup Placing Simulation c. Depiction of a single subject training with and without haptic effects on Day one. Dashed line is training with no added damping or gravity assist. Thick line is training with damping and gravity assist. d. Same subject after eight days of training with haptic assistance, performing cup placing with no damping or gravity assist. Note the up and over trajectory comparable to a real world placing task.

a trajectory that accommodates the spatial aspects of the placing movement (see thick line near the shelf). However, Figure 3.2d shows that after two weeks of training this subject demonstrated more normal hand trajectories of placing cups on the shelf, even without haptic assistance. Detailed performance data for each subject is listed in Appendix C.

Real-world upper extremity function was measured using the 15 timed items from the Wolf Motor Function Test (WMFT), an outcome measure utilized in the EXCITE trial, one of the largest trials of upper extremity rehabilitation in the stroke literature [32]. This group of tests consists of simple movements and standardized functional activities which are timed. Each activity has a 120 second time limit and subjects that are unable to complete an item are given a score of 120. The WMFT also contains two strength measurements which were not collected. Results from the WMFT are summarized in Appendix D. Subjects' pretest scores ranged from 54.4 seconds to 179.6 s (Mean (SD) = 111.8 (60.9)). Post-test scores ranged from 50.5 s to 187 s (Mean (SD) = 96.2 (63.2)). Pre to post-test percentage change ranged from -4% to 40% (Mean (SD) = 13.7 (19)). Two subjects improved their aggregate time to complete all 15 timed items by more than 10%.

3.2 Feasibility Study with Children with Cerebral Palsy

One of the limitations of existing therapeutic VR systems for children with CP is the relatively high level of motor function required to interact with these systems [53]. One approach to broadening the group of people that can utilize VR and gaming technology for motor rehabilitation has been combining virtual environments with adaptive robotic systems. These systems have been studied in the adult stroke population [43, 76, 77].

Recently, a single investigation into the use of robots for upper extremity rehabilitation for a child with CP was presented by Fasoli et al [78]. They describe a case study with a six year old child with upper extremity hemiplegia that performed four weeks of robotically facilitated planar reaching activities following application of botulinum toxin to reduce spasticity in elbow, wrist and finger flexors. This subject showed small improvements at the impairment level that were comparable to the effects of an equivalent volume of Occupational Therapy following botulinum toxin therapy and a corresponding increase in parent ratings of spontaneous use of the involved arm and hand.

The hypothesis is that the integration of VR with robotics could be successful if applied to children with hemiplegic CP. The combined benefits of increased attention provided by VR and the large training stimulus afforded by adaptive robotics demonstrated in the stroke rehabilitation literature [42, 76, 77, 79, 80], may increase the beneficial effects of these two approaches synergistically.

3.2.1 Participants

Two children, a seven year old girl (S1) and a ten year old boy (S2), both with spastic hemiplegia secondary to Cerebral Palsy (CP) were recruited from the outpatient department of a comprehensive pediatric rehabilitation facility. The children were chosen based on an ability to attend to all items on a 16 inch wide screen, demonstrate at least minimal active movement of their shoulder and elbow and tolerate at least 90 degrees of passive shoulder flexion. Pre-participation data is summarized in Table 3.2. All relevant information was obtained from medical records or a questionnaire completed by parents of the participants.

Table 3.2 Cerebral Palsy Pilot Study Subjects Characteristics

Subject	Age	Sex	Cognition	Impaired Hand	Dominant Hand	Ambulatory?
S1	7	F	Normal	Right	Left	No
S2	10	M	Normal	Left	Right	No

3.2.2 Training Procedure

Participants used the Robot Assisted Virtual Rehabilitation (RAVR) system for one hour, three days a week for three weeks in order to approximate a short course of outpatient therapy. Subjects performed four sets of ten reaches utilizing the Bubble Explosion simulation to initiate each session for performance testing purposes. The subjects played a combination of three or four of the other simulations depending on their therapeutic goals, tolerances and preferences for the remainder of the sixty minute session. This resulted in an average of 23 minutes of activity during the 60 minute sessions for S1 and S2. Games were modified gradually to increase difficulty in order to challenge the subjects as their performance improved. Initially subjects attempted to utilize compensatory movements to accomplish the game tasks as observed visually by therapists monitoring training. Splinting and positioning adjustments were made by the therapists to enhance typical movement patterns. In addition the starting positions and parameters (beginning AROM, resistance, and damping) on the RAVR were modified in order to physically challenge the subjects but allow for an approximate success rate of 80%. Cumulative motor fatigue was observed at varying points during training. At these points, the therapists adjusted activity parameters to prevent unintended muscle substitution patterns and to maintain approximately 50% of continuous participation for the 60 minute training session. Task parameters from the final trial of the previous session were used to initiate training for subsequent sessions.

3.2.3 Measurements

Clinical testing was performed just prior to and immediately following the training period. The same licensed / registered Occupational Therapist performed both sets of clinical tests using the same equipment. Measurements included upper extremity active range of motion and strength. Upper extremity movement quality was measured using the Melbourne Assessment of Unilateral Upper Limb Function (MAUULF), a 16 activities battery designed for children with upper extremity hemiplegia [81]. Each activity is rated on a three, four or five point scale with all 16 activities summed to achieve a raw score. The raw score is divided by the total possible score to produce a percentage score [75, 82]. Three of the tests included in the Melbourne Assessment including forward and lateral reaches and a hand to mouth reach were timed to assess changes in motor control and real-world upper extremity function. Kinematic measurements including hand movement speed and movement duration were calculated using data collected by the robot during the Bubble Explosion activity on the first and the last day of training as well as at the first day of each training week. Smoothness of endpoint trajectory during performance of the same activity was evaluated by integrating the third derivative of the trajectory length. This numerically describes the ability to produce smooth, coordinated, gross reaching movements versus disjointed collections of sub-movements [83, 84]. Four Nest of Birds ™ sensors were attached to the wrist, elbow, shoulder and trunk of the participants to measure the kinematic parameters of the impaired limb at a sampling rate of 100Hz.

Subjects responses to the simulations were evaluated via survey and therapist report each session. Therapists determined if a subject showed fatigue during a simulation and if the subject maintained attention throughout performance of a simulation. Time to fatigue and time to break in attention was also recorded. After each simulation subjects were asked if a simulation was fun and if they would like to perform the simulation again in the future. Yes, Maybe, and No responses were recorded.

Table 3.3 Melbourne Test

	MAUULF %		Forward Reach (s)		Reach sideways (s)		Hand to Mouth (s)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
S1	59.8%	67.2%	2.9	1.5	2.2	0.8	5.4	4.6
S2	76.2%	77.1%	4.5	1.5	2.4	1.8	2.2	1.6

3.2.4 Results

Both participants completed nine hours of training in three weeks. No untoward events occurred and no adverse responses to treatment or complaints of cyber sickness were reported. The games in general held the children's attention for an entire sixty minute session. Specifically, the Bubble Explosion game and the car game were more motivating to the children which allowed greater participation.

Subject S1 showed improvements in their overall performance on the Melbourne assessment (Table 3.3), with the overall percentage score increasing from 59.8 to 67.2. She demonstrated improvement on all of the MAUULF items involving upper extremity elevation except hair combing, which correlates with her improvements on the three timed components of the Melbourne Assessment (Table 3.3). She also improved in the" hand to mouth and down" item but did not improve on the pronation-supination item despite her improvement in supination AROM. Subject S2 did not demonstrate improvements in the "Forward…" or "Sideways Reaching to an Elevated Position" items from the MAUULF despite improvements in speed during these movements. He scored higher initially than S1 on these items possibly suggesting a ceiling effect on sensitivity."Reaching to opposite shoulder" performance improved, as did "hand to mouth and down "performance. His MAUULF pronation-supination score did not change, despite a large improvement in supination AROM. S2 only improved 0.9 percent on his MAUULF composite score but made substantial improvements in active range of motion (Table 3.3) and kinematic measures of his performance on the Bubble Explosion reaching activity (Table 3.5). S2 achieved a 15 degree increase in active shoulder flexion (from 130 to 145), and a 50 degree increase on forearm supination (from -60 to -10). No standards for clinically significant change as they relate to active range of motion

Table 3.4 Impairment Measurements

Subject	Strength						Active Range of Motion					
	Grip		Lateral Pinch		3-Jaw Pinch		Shoulder Flexion		Elbow Flexion		Supination	
	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post
S1	6	14	3	7	1	2	150	145	140	140	0	0
S2	3	3	2	4	1	2	130	145	140	140	-60	-10

measurements in this population have been established, but the impact of range of motion impairments on function in children with CP is supported by the rehabilitation literature [84, 85].

Both S1 and S2 had an almost 100% increase on strength tests. S1's grip strength increased from 6 lbs to 14 lbs, lateral pinch strength increased from 3 lbs to 7 lbs, and 3-jaw pinch strength increased from 1 lb to 2 lbs. S2's lateral pinch strength increased from 2 lbs to 4 lbs, and 3-jaw pinch strength increased from 1 lb to 2 lbs. These gains are

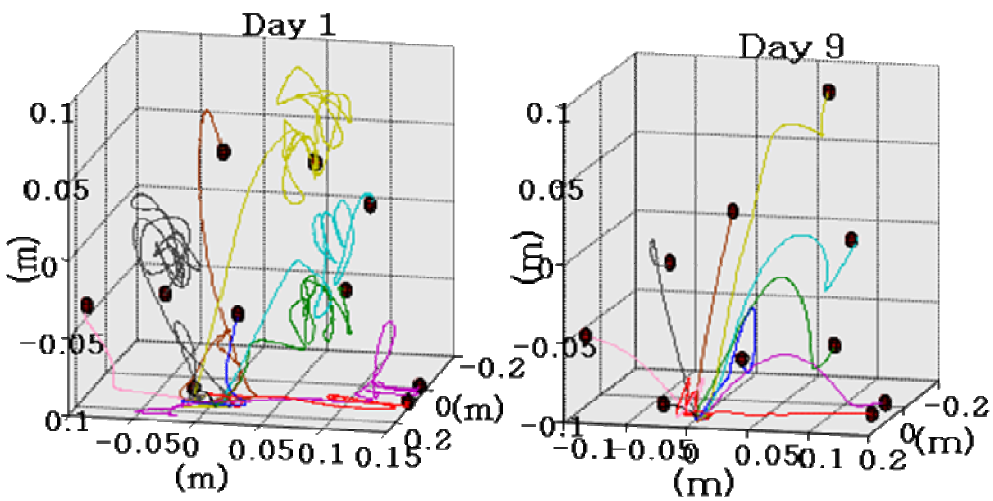


Figure 3.3 Hand trajectories performed to accomplish this task on day one and day nine by subject S2.

interesting based on the fact that grip and hand strength were not specifically trained during the intervention. Similar improvements of smaller magnitude in distal function in response to proximal upper extremity robotic training have been described in the adult stroke literature [55].

Both participants showed improvement on several kinematic measures of the movement recorded directly by the robot, during the Bubble Explosion activity. Figure 3.3 demonstrates the hand trajectories performed to accomplish this task on day one and day nine by subject S2. Trajectories became more accurate and stable. The percentage of improvement between pre-test and post-test for several kinematic measures including smoothness, a measurement of the ability to perform a single well-integrated movement, and two measures of efficiency (path length and duration) are shown in Table 3.5. The improvements in stability and accuracy demonstrated by S2 in Figure 3.3 are supported by improvements in these analyses (Table 3.5). S1 made similar improvements between day 1 and 6 but failed to maintain them over the entire length of the study period. S1 began school after her sixth training day and was unable to perform at the level she previously achieved following a full day of school.

Table 3.5 Percentage Change in ReachTouch Kinematics

	Duration	Path Length	Smoothness
S1	0.94%	18.02%	-0.99%
S2	68%	64%	92%

Subject response data for two of the simulations proved to be interesting. Hammer Task and Car Race both train supination, an area of impairment for both subjects, but subject response to the two simulations differed. Both subjects performed Hammer Task four times. S1 demonstrated decreased attention in two of the four sessions with this simulation and fatigue in three of the four sessions. S2 demonstrated decreased attention during three of his four sessions and fatigue during four of his sessions performing the

Hammer simulation. Neither subject described the activity as fun and never agreed to perform the simulation again in the future. However, both subjects agreed to try the simulation again during subsequent sessions and both subjects demonstrated gradual increases in tolerance for the activity. In contrast, the Car Race simulation proved to be the most popular simulation with no attention lapses, no demonstrations of fatigue and unanimous agreement that the simulation was fun and an option for future sessions. The other simulations did not display a consistent response pattern.

3.3 Conclusions

All of the pilot subjects were able to perform training, even if they had difficulty with these types of activities in real world environments. And all of them experienced improvements in kinematic measures during their robotic training activities. The combination of assistance modes, scalable workspaces and hand-robot interfaces, allowed subjects to train multiple joints in three dimensions without extensive support of their upper extremity.

One of the dilemmas in robot-assisted rehabilitation is to indentify an optimal combination of two approaches to facilitation of motor skill recovery. The first approach uses the robot as a “teacher” with the objective to teach the patient, for the given motor goal, an optimal hand trajectory and/or pattern of inter-joint coordination. The second approach uses the robot as an “enabler” that provides the minimal assistance needed for the patient to accomplish the motor task. In the first case, the robot usually guides the subject along the desired endpoint trajectory or restricts the subject’s movement away from this trajectory. Two methods of implementing this second strategy include, the "bead" approach which is based on minimum jerk trajectory control [65, 66], as well as the use of a haptically rendered channel, described by Krebs et al. [58]. Both of these approaches limit deviation from predetermined trajectories and utilize extensive external support of the arm. The optimal amount of this type of guidance for maximizing recovery facilitation is not known. An important challenge when using this approach is to avoid making the patient's experience primarily passive, which would decrease the therapeutic effect [36]. One solution would be to reduce the stiffness of the controller to allow for larger deviations from the desired trajectory. The admittance-based controller of the robot allows for generation of high forces to create stiff virtual surfaces that can either guide or restrict hand motion in 3D space. This feature can be used to restrict subject's movement to a vicinity of a target trajectory, for example, by creating a virtual "tube" centered on the planned trajectory (not analyzed in this study). Another possible strategy would be to amplify subject's deviations from the desired trajectory in order to augment the error detection abilities of participants or exploit aftereffects [86].

An additional approach would be to use haptic virtual environments to shape the hand trajectories more indirectly. The ability of the admittance controlled robot to generate precise haptic effects allows the creation of high-fidelity virtual objects, for example, the haptic shelves utilized in the cup placing simulation, and the ramp utilized in the reach-touch simulation. This offers a physical method of shaping 3D trajectories of the arm, important for transfer to real world transport/reaching activities. Providing a haptically rendered environment forces the participant to form an internal model of the virtual environment and adapt their own self generated motor programs to fit this internalized model [87]. The ability to generate, implement and fine tune motor programs within physical task constraints is an important skill set critical to independent function.

Another important aspect of human-robot interaction during rehabilitative training would be the goal of minimizing the robotic assistance and to provide it only “as needed” [43]. In author’s approach the subject moves with limited external support and generates trajectories independently, with the objective to avoid the typically occurring human “slacking” associated with extensive external assistance [88]. Variable stiffness springs can be utilized to maintain an acceptable rate of progress toward movement objectives, in combination with other haptic effects such as antigravity assistance, stabilizing damping or haptically rendered obstacles that can be employed at the discretion of a therapist to train optimal trajectories. Minimizing external assistance to the smallest degree required for task completion during practice and adaptively increasing the difficulty level of the practiced tasks are consistent with the theories of motor learning applied to stroke rehabilitation [89].

CHAPTER 4

STROKE PATIENTS RAVR TRAINING STUDY

4.1 Introduction

Studies involving, rodents, non-human primates and humans report that the repetitive practice of motor activities increases the area and density of cortical areas corresponding to the practiced movement [8-10]. Several patterns of expansion have been described, including the sharing of overlapping cortical space with adjacent representations or through a use dependent competition between these adjacent representations. This phenomenon of use dependent plasticity could provide a tentative rationale for the relatively poor recovery of hand function as compared to arm function described in persons with similar levels of impairment immediately after their strokes [90, 91]. A mutually inhibitory relationship between proximal and distal UE effectors in persons with stroke has been demonstrated experimentally [7]. A similar inhibitory relationship has been proposed to exist between right and left effectors [92]. Studies have shown that the inhibitory relationship between right and left effectors may be modified though coordinated training of both arms at the same time [93]. Could this concept of simultaneous, coordinated movement also be used to modify the inhibitory relationship proposed to exist between proximal and distal UE effectors in persons with stroke? Would training the hemiparetic upper extremity in an integrated and coordinated fashion result in more balanced, positive cortical adaptations and more effective recovery of hand use? A system has been designed using adaptive robots, integrated with virtual targets or complex virtual reality gaming simulations in order to provide such multi-faceted training. Several small studies using robots, to provide coordinated movements of the

Table 4.1 Stroke Subjects Characteristics by Group

	HAT group N=20	HAS group N=20	Control Group N=12
Age	56.0	53.2	50.6
Gender	15/5	14/6	8/4
Handedness	16/4	19/1	12
Effected side	10/10	13/7	7.5
Time since onset (months)	70.2(±66)	61.4(±47)	80.5(±59)
Chedoke McMaster arm stage (6)	5.35 (±1)	5.15(±1)	5.33(±1)
Chedoke McMaster hand stage (6)	4.35(±1)	4.1(±1)	5.17(±1)
Initial WMFT time (s)	95(±66)	126(±112)	70(±32)
Initial JTHF120 time (s)	125.4 (±53)	141.2(±53)	101.9(±47)
Initial JTHF 45time (s)	89.1(±75)	87.2(±52)	97.2(±40)

Gender (M/F), Handedness(Rt./Lt.), Effected Side(Rt./Lt.)

hand and arm have produced mixed results [55, 94, 95]. This paper will describe initial results from an on-going clinical trial using a haptic, six degrees of freedom robot and virtual environments to compare integrated training of the hand and arm together (HAT) and isolated training of the hand and arm separately (HAS). An important question is whether these different training paradigms produce different motor learning dynamics and/or different outcomes.

4.2 Methods

4.2.1 Subjects

A total of 52 stroke subjects participated in the study. Twenty subjects (mean age=53.2; months post stroke =61.4(±47)) practiced approximately three hours/day for 8 days on simulations that trained the arm and hand separately (HAS). These simulations included Piano1, Space Pong, Reach Touch, Cups, Hammer (pronation/supination) and Blood Cell. Twenty subjects (mean age=65.0; months post stroke =70.2(±66)) practiced for the same amount of time on simulations that trained the arm and hand together (HAT), which included Piano2, Hammer (finger extension), Hummingbird Hunt and Plasma Pong. Twelve subjects (mean age=50.6; months post stroke=80.5(±59)) received traditional physical therapy of similar intensity and duration. Subjects' characteristics averaged by group are listed in Table 4.1.

4.2.2 Outcome Measurements

To assess the effectiveness of robot training and to compare improvement across the three groups, three types of the outcome measurement were conducted. They are robot measurements, Reach to Grasp kinematics measurements and clinical assessments.

Robot measurements were based on the real time movement tracking during the training. These measurements were generated by the robot, by the data gloves and magnetic tracking system at the rate of 100 Hz. For Piano training, each finger displacement was calibrated and tracked by the CyberGlove™. Hand movement was

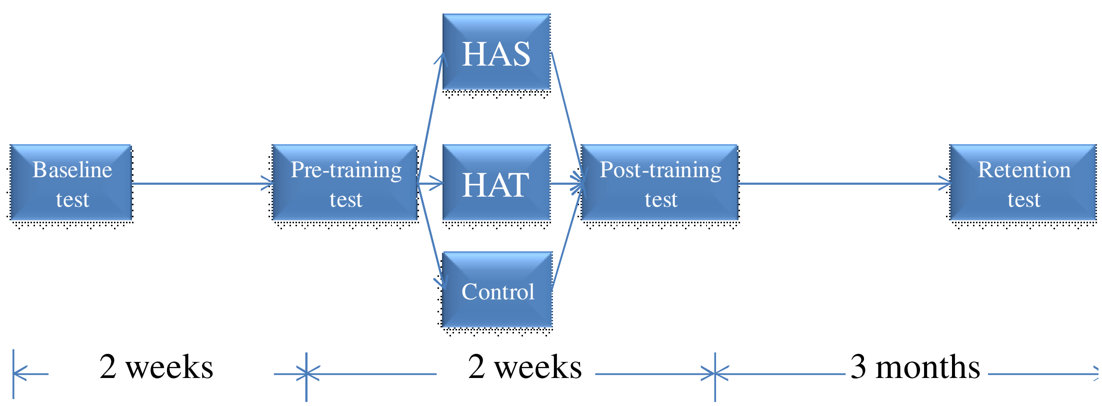


Figure 4.1 Training and outcome measurements diagram.

recorded by the electromagnetic tracking system. For robot training, hand position, velocity and forced applied to robot were recorded by the HapticMaster™ in real time. The offline data analysis included calculations of Movement Duration, Trajectory

Length, Movement Smoothness, Arm Stability (Hammer), Finger Fractionation and Accuracy (Piano).

Repeated measures analyses of variance (ANOVA) were performed to compare changes between two groups. Paired t-tests were performed to find significant changes in each of the above kinematic variables before and after RAVR training.

Reach to Grasp test was used to evaluate changes at the activity level of an untrained UE movement [96]. At the beginning of the Reach to Grasp test, patients were seated while their arm and hand were resting on a predefined location on a table. Shoulder was about 30 degree abducted and elbow was about 90 degree flexed and 45 degree inward rotated. Four Objects of two different sizes (small and big), and two different shapes (round and rectangular) were placed at about 30 centimeters from the

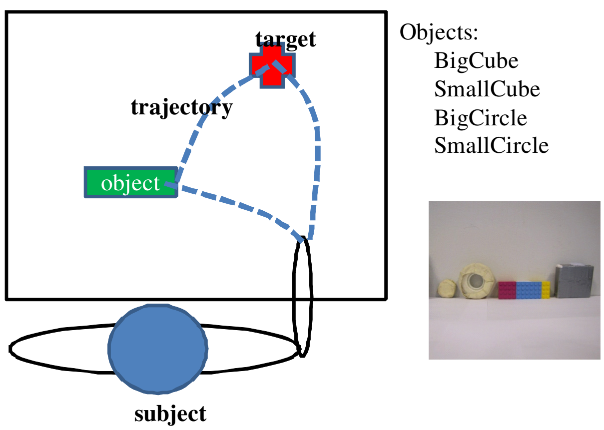


Figure 4.2 Schematic of the ReachGrasp test. Insert: photo of the objects.

patients. Subjects were asked to reach for the object from the resting position, grasp it with the fingertips and put it on the top of a five centimeters high box at a comfortable speed. (Figure 4.2). A 'Ding' sound was generated by the computer to signal patients to start the movement. Subjects were instructed to grasp round shape object with five fingertips spreading out equally around edge of the object. To grasp rectangular shape object, subjects were asked to put four fingertips at one side of the block and the thumb on the opposite side. The subjects' unimpaired and impaired arms were tested at both pre-training and post-training data collection sessions. Subjects' trunk, shoulder, elbow and wrist were monitored and recorded using trackSTAR motion sensors. Subjects' hands shape was tracked using the CyberGlove™.

Clinical assessments were conducted to test for changes at the activity level. Combination of the Wolf Motor Function Test[72], the Jebsen Test of Hand Function [97] and the Nine Hole Peg Test [98] were utilized. This combination was chosen in order to capture change in the ability to perform gross and fine motor movements. Both Reach to Grasp test and the clinical assessments were performed two weeks before the training, one day before the training and three days after the training. Clinical assessments were also performed three months after the training as shown in Figure 4.1.

4.3 Results

Results presented in this dissertation will be divided into three categories: daily real time kinematics data for each training activity, outcome measurements changes between pre and post training, and comparison across the three groups based on Hammer and Piano data and outcome measurements.

4.3.1 Robot Measurements

A total of 20 HAS and 20 HAT subjects completed the two weeks of training. Two subjects from the HAS group did not participate in the Hammer simulation because the simulation was developed after their training was finished. Data from both HAS and HAT group was recorded at 100Hz during the training and saved in the corresponding directory for offline analysis. Robotic kinematics was not available for the control group because of the non-automated / instrumented nature of their training. The following three sections describe the results from each training simulation.

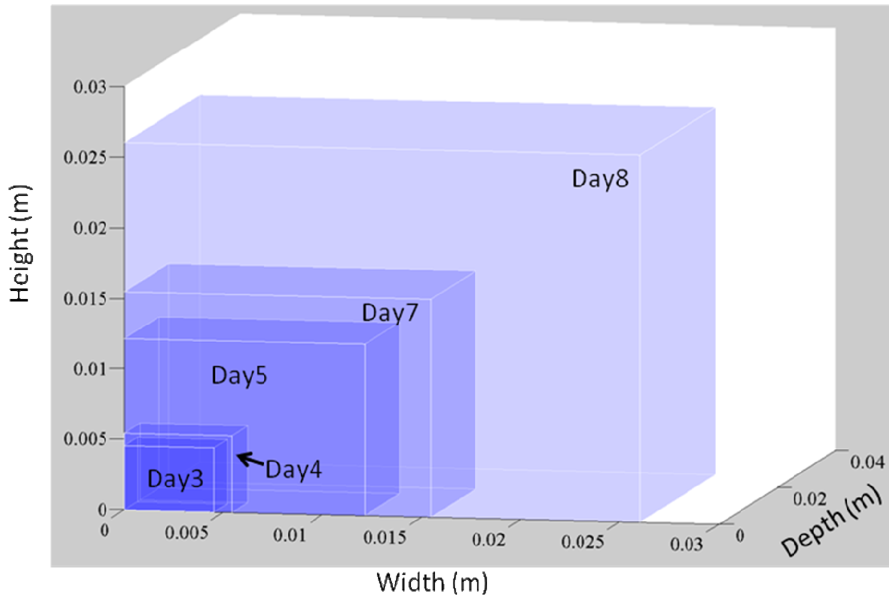


Figure 4.3 Work space expands continuously and gradually throughout the training period.

4.3.1.1 ReachTouch ReachTouch was a training simulation for HAS group. The goal of the ReachTouch game is to improve forward, sideways and overhead reaching ability. There is no finger motion involved. To adapt each subject's range of arm motion, the ReachTouch work-space size was calibrated for each subject at the first day of each training week to record subject's range of motion. During training, workspace was started from 60 percent of the calibrated workspace, and gradually increased to 100 percent at the end of the week. Figure 4.3 shows an example of work space volume change for S19. Workspace size of day 3 and day 4 were 60% and 80% of the first week's calibration range. Workspace size of day 5, day7 and day 8 were 60%, 70% and 90% of the second week's calibration range. Work space volume expanded continuously and gradually throughout the training period. The reason to start from small workspace then move to the bigger one was to keep the simulation at a reasonably challenging level.

Table 4.2 ReachTouch Kinematic Changes on the First and Last Day

SUBJECT	DURATION		PATH LENGTH		SMOOTHNESS	
	FIRST	LAST	FIRST	LAST	FIRST	LAST
HAS1	2.7675	1.5580	0.3253	0.3189	320.8524	311.8110
HAS2	2.4345	1.5870	0.2486	0.2186	211.8448	78.6877
HAS3	8.8672	2.1908	0.3598	0.1922	8034.1548	230.2756
HAS4	10.4127	2.8653	0.5773	0.2023	10654.3340	1269.1216
HAS5	4.5603	2.1060	0.2233	0.2496	1056.3084	167.7566
HAS6	3.9608	2.8006	0.2542	0.1931	1573.7291	644.8269
HAS7	5.2799	2.4229	0.2217	0.2220	8795.3095	432.5973
HAS8	4.4162	1.5752	0.2689	0.2411	1318.4889	115.3171
HAS9	4.1308	2.3582	0.2389	0.2259	979.8718	441.9636
HAS10	2.9727	2.0544	0.3360	0.2698	738.9797	368.6213
HAS11	14.0377	11.1740	0.2160	0.1948	7487.5076	7702.0296
HAS12	9.5076	3.4299	0.4697	0.4046	3552.9431	998.9546
HAS13	12.1977	3.9750	0.3354	0.2037	14037.7520	1299.2457
HAS14	7.4020	6.1161	0.4948	0.2222	5856.7828	3020.1289
HAS15	5.3351	1.2167	0.5198	0.3032	1684.3750	195.7113
HAS16	10.6689	4.0072	0.3919	0.2163	5647.6555	603.4500
HAS17	9.5553	5.4502	0.2737	0.2544	4469.7115	1750.8689
HAS18	13.1400	6.6169	0.5212	0.2705	13039.8490	3116.7731
HAS19	6.8335	2.6792	0.2837	0.2864	3172.4032	398.3980
HAS20	21.1447	5.5292	0.6464	0.3045	47128.0780	2249.6588

Duration is measured as the average time that elapses during reaching of each sphere from the starting point. Therefore, the measurement of duration for these activities offers insight into the efficiency and accuracy of the subjects' arm movements. Path Length is measured as the accumulated trajectory length subject traveled from the starting point to each sphere. Smoothness of the trajectories is evaluated by integrating the third derivative of the trajectory length, calculated as:

$$NIJ = \sqrt{\frac{T^5}{2L^2}\int_o^T J^2 dt} \qquad (1)$$

Where T= duration, L = Length of trajectory, $J = \frac{d^3L}{dt^3}$, NIJ = *normalized integrated jerk.*

This numerically describes the ability to produce smooth, coordinated, gross reaching movements without object manipulation versus disjointed collections of sub-movements [75, 82, 85]. Rohrer et al [99] cite this ability as an indicator of neurological recovery in persons with strokes. Figure 4.4 shows average daily changes in Duration and Path Length for 20 HAS subjects. Average duration to reach each target gradually decreased from day one to day eight as well as the trajectory length. Standard deviation is also decreased. Table 4.2 shows average Movement Duration, Path Length and

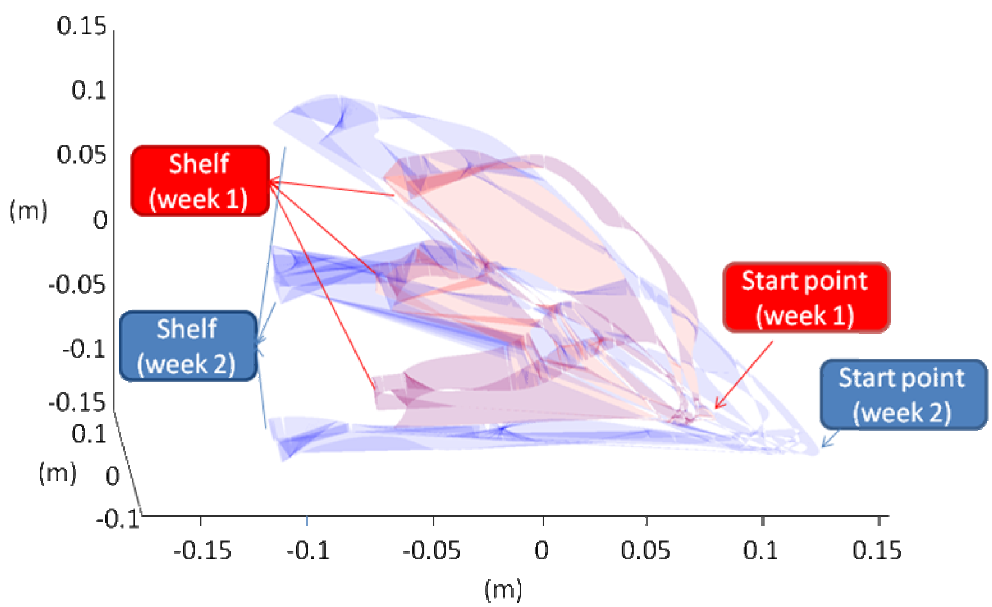


Figure 4.5 Cups simulation workspace changes after two weeks of training (data from S19).

Smoothness for 20 HAS subjects on the first and last day of training. HAS group made 55.1% decrease in Duration from 7.981 s to 3.586 s ($F(1,18)=13.66$, $p=0.001$), 30.4% decrease in Path Length from 0.3603 m to mean=0.2497 ($F(1,18)=11.99$, $p=0.001$) and 81.8% decrease in Smoothness from 6988 to 1270 ($F(1,18)=5.91$, $p=0.02$).

4.3.1.2 Cups Cups is the training simulation for HAS group. The goal of the

Table 4.3 Cup Kinematics Change in First and Last Day

SUBJECT	DURATION		PATH LENGTH		SMOOTHNESS	
	FIRST	LAST	FIRST	LAST	FIRST	LAST
HAS1	3.8471	2.4838	0.5375	0.5224	668.9890	455.4325
HAS2	3.9428	2.9108	0.4177	0.4784	1458.1481	401.0257
HAS3	8.4148	2.9324	0.5806	0.3459	3280.9252	297.6832
HAS4	8.1007	2.8431	0.4739	0.1680	3053.4589	208.9075
HAS5	8.5100	2.4946	0.5833	0.3667	3289.0515	189.8400
HAS6	4.0000	2.3113	0.5325	0.2655	804.5472	225.6333
HAS7	3.8919	2.1562	0.4291	0.3153	669.9505	585.9738
HAS8	9.3080	1.7776	0.8318	0.3972	5706.2677	245.4659
HAS9	8.4278	2.3366	0.8605	0.3194	2519.7081	240.5073
HAS10	5.7603	1.5224	0.6091	0.2859	1861.4852	126.0950
HAS11	4.7033	2.0317	0.3739	0.2998	1719.4256	154.9208
HAS12	4.4622	1.9391	0.3424	0.2882	513.5691	138.8572
HAS13	4.2053	1.7657	0.2297	0.2040	1425.4753	334.7499
HAS14	3.6394	3.7767	0.4289	0.1884	709.7897	652.7290
HAS15	4.2025	2.4378	0.5455	0.3976	798.3258	235.4589
HAS16	5.2907	3.0289	0.4943	0.1917	552.5745	240.8563
HAS17	5.8223	3.4712	0.2531	0.1993	1035.7033	274.7047
HAS18	6.2062	3.4926	0.4225	0.2554	2300.2283	525.4741
HAS19	2.5602	1.8190	0.2488	0.3150	267.7080	118.4016
HAS20	15.0441	4.1864	0.4426	0.2142	20073.7840	1012.0031

Table 4.4 Hammer Kinematics in First and Last Day for HAS Group

SUBJECT	DURATION		PATH LENGTH		SMOOTHNESS		ARMFIXATION SCORE	
	FIRST	LAST	FIRST	LAST	FIRST	LAST	FIRST	LAST
HAS3	20.68	15.00	1.21	0.83	20357.07	10894.97	60.49	67.17
HAS4	24.67	14.76	0.99	0.57	67148.28	18156.49	71.30	30.21
HAS5	13.57	9.44	0.68	0.48	62714.51	3607.76	49.38	28.40
HAS6	24.94	23.60	2.15	1.05	29827.26	21666.71	50.66	36.56
HAS7	20.56	10.67	1.18	0.80	13049.53	4038.35	50.15	37.94
HAS8	26.83	11.97	1.61	0.74	33362.34	10656.80	30.36	47.60
HAS9	38.69	13.55	1.42	0.79	44472.14	13636.94	59.90	43.76
HAS10	23.33	14.57	2.33	1.85	26387.56	7806.78	68.50	51.12
HAS11	25.77	11.06	0.73	0.70	21701.67	9035.02	44.31	54.41
HAS12	19.83	11.84	0.98	0.79	11684.77	8403.95	64.76	80.69
HAS13	18.79	16.40	0.79	0.80	46416.92	39818.41	15.87	15.55
HAS14	93.24	11.93	3.68	0.32	463313.70	16.31.33	n/a	n/a
HAS15	62.00	5.77	2.20	0.73	203359.54	2331.66	80.49	70.09
HAS16	29.60	13.14	1.23	0.44	24849.95	4967.79	13.78	4.13
HAS17	25.05	17.13	0.74	0.57	20057.91	8083.15	10.28	6.50
HAS18	41.03	15.09	1.32	0.69	109117.86	9948.60	22.06	5.48
HAS19	8.45	7.16	0.39	0.44	3137.11	2603.40	2.53	2.83
HAS20	68.36	12.27	2.06	0.48	317812.70	7438.78	70.27	5.98

Cups game is to improve forward, sideways and overhead reaching ability. There is no finger motion evolved.

Workspace for Cup simulation was calibrated every week at the beginning of the training. As shown in Figure 4.5.shelf location to where subject put on cups is further and higher in the second week (in blue) than the first week (in red). Figure 4.6 shows average daily change of Duration and Path Length over 20 HAS subjects. Table 4.3 listed 20 HAS subjects' first and last day of movement duration, Path Length and smoothness. As a group, 20 HAS subjects made significant 58% decrease in Duration from 6.017 s to 2.586

s ($F(1,18)=26.13$, $p<0.001$), 37.6% decrease in Path Length from 0.4819 m to 0.3009 m ($F(1,18)=17.59$, $p<0.001$) and 87.4% decrease in Smoothness from 2635 to 333 ($F(1,18)=5.67$, $p=0.022$).

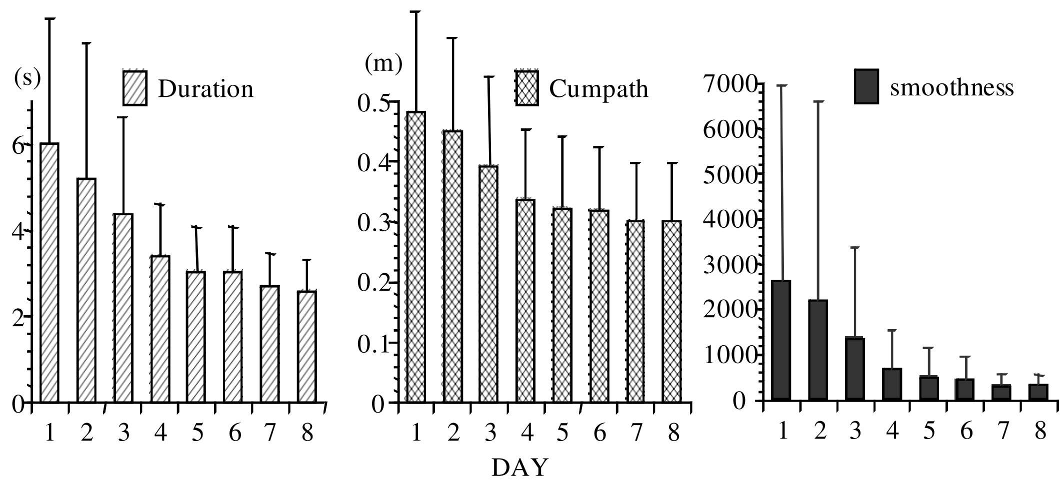


Figure 4.6 Average daily change of duration, Path Length and Smoothness over 20 HAS subjects from the Cup simulation.

4.3.1.3 Hammer This simulation trains a combination of three dimensional reaching and repetitive forearm pronation and supination in HAS protocol or repetitive finger flexion and extension in HAT protocol. Duration is the average time the subject took to reach the target peg and hammer it down to the ground. Path Length is the accumulated

Table 4.5 Hammer Kinematics in First and Last Day for HAT Group

SUBJECT	DURATION		PATH LENGTH		SMOOTHNESS		ARMFIXATION SCORE	
	FIRST	LAST	FIRST	LAST	FIRST	LAST	FIRST	LAST
HAT1	32.87	20.14	1.13	0.76	45255.46	19323.76	99.02	50.35
HAT2	25.39	16.62	1.21	0.74	35272.63	14615.70	137.30	54.13
HAT3	16.34	8.00	1.01	0.59	10023.07	2614.00	49.61	32.68
HAT4	36.97	21.81	1.61	0.85	76321.78	30439.31	123.60	76.80
HAT5	24.02	16.57	1.60	1.08	79441.94	33727.37	73.16	61.85
HAT6	23.93	8.43	1.23	0.49	35698.81	3929.23	97.71	29.77
HAT7	24.43	16.29	1.39	0.72	24226.90	8271.50	111.91	83.30
HAT8	30.86	11.81	1.29	0.56	42774.07	5365.35	97.31	29.87
HAT9	101.51	19.52	5.25	0.75	1022117.60	24574.78	389.20	14.43
HAT10	23.41	10.87	0.81	0.53	18187.93	3166.44	67.63	52.32
HAT11	100.93	31.24	3.52	1.19	458733.39	71141.65	274.65	70.63
HAT12	9.23	4.13	0.40	0.31	3779.05	436.08	4.57	1.79
HAT13	45.90	104.07	2.97	6.62	134055.26	448701.66	165.15	283.12
HAT14	53.84	14.72	1.34	0.49	162751.94	28326.02	22.60	2.90
HAT15	18.95	15.65	0.72	0.51	30857.71	13022.03	10.31	6.17
HAT16	13.15	4.08	0.42	0.24	12459.18	755.20	4.00	0.45
HAT17	15.66	9.44	7.52	6.97	7.11	6.34	6.43	5.56
HAT18	51.22	10.27	1.19	0.26	89099.69	2439.18	47.45	1.40
HAT19	44.24	6.45	2.18	0.43	146364.76	1553.51	81.00	5.25
HAT20	25.98	19.29	0.78	0.78	33836.383	12397.506	13.12	7.83

trajectory length from the starting point to the target. Arm fixation score is calculate with the accumulated distance between the actual endpoint position and target location, normalized with time. It is a measure of proximal stability and shoulder stabilization. Because Hammer is a new simulation developed in the middle of study, there are only 18 HAS and 20 HAT subjects has data for this simulation. Table 4.4 and 4.5 listed the first and last day of movement duration, Path Length and smoothness. S14 from HAS from didn't have ArmFixation score because her impaired arm was too weak to stay on the top of the peg. In order to let her complete the training, robot was used to support her arm at

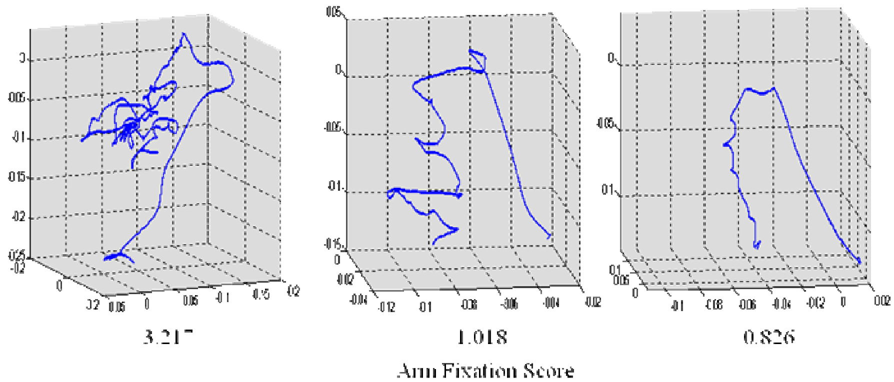


Figure 4.7 Arm Fixation score. The smaller score the better shoulder control and arm stability.

two different fixed locations (near and far), she pronated and spinated the forearm to hammer down the peg without moving her arm.

Figure 4.7 show the example of arm fixation score from difference performance, the lower score the better stability. Figure 4.8 shows average daily change of Duration, Path Length and ArmFixation Score from18 HAS subjects.

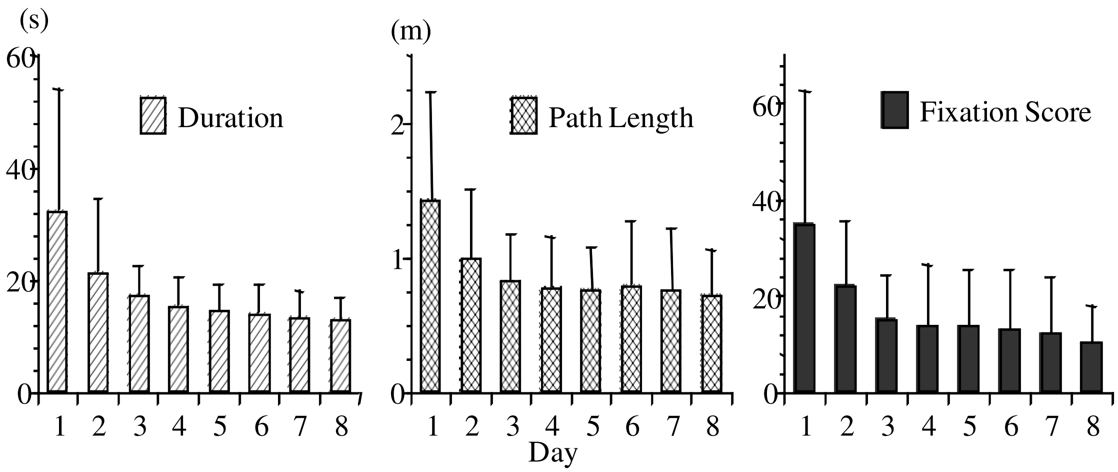


Figure. 4.8 Left and middle figures show the average daily change of Duration and accumulated trajectory length. Right shows the average daily change of arm fixation score for HAS group.

Compared between the first and last day of training, there are significant improvements in Duration (first day: mean=32.521s, SD=21.514; last day: mean=13.075 s, SD=3.967; F(1,18)=13.480, p=0.0019), Path Length (first day: mean=1.428 m, SD=0.803; last day: mean=0.726, SD=0.334; F(1,18)=13.405, p=0.0019), Smoothness (first day: mean=84376.157, SD=123258.090; last day: mean=11062.605, SD=8931.287; F(1,19)=6.360, p=0.0219) and ArmFixation (first day: mean=35. 211, SD=27.399; last day: mean=10.544, SD=7.500; F(1,19)=15. 113, p=0.0013).

Figure 4.9 shows average daily change in Duration, Path Length for 20 HAT subjects. They showed significant improvements in Duration (first day: mean=36.465 s, SD=26.120; last day: mean=18.222 s, SD=21.913; F(1,19)=7.631, p=0.013), Path Length (first day: mean=1.565 m, SD=1.201; last day: mean=0.921 m, SD=1.403;

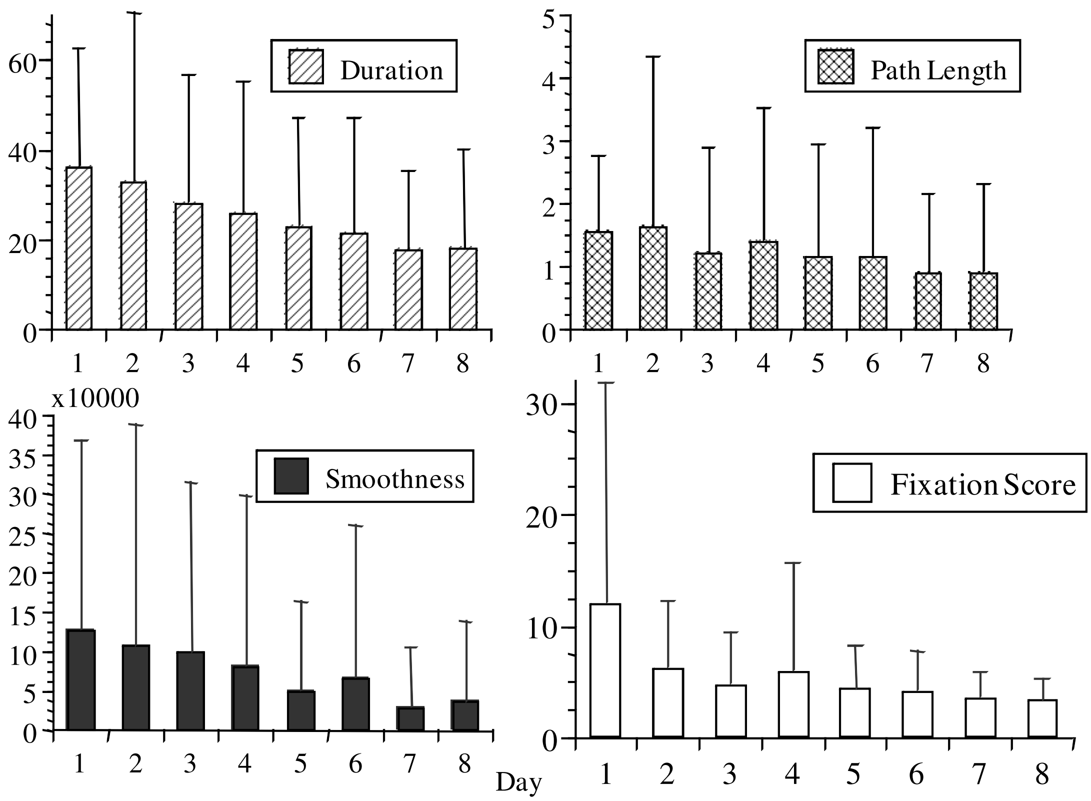


Figure 4.9 Average daily changes in Duration, Path Length, Smoothness and ArmFixation Score for the HAT group.

F(1,19)=3.639, p=0.073), and ArmFixation (first day: mean=98.089, SD=96.826; last day: mean=45.300, SD=64. 190; F(1,19)=5.495, p=0.031) as well. HAT group showed has improvement in smoothness (first day: mean=128158, SD=230097; last day: mean=37540, SD=101100) but not significant.

4.3.1.4 Piano The piano trainer was designed to help improve the ability of subjects to move each finger in isolation, either during arm motion or in the absence of arm motion. The simulation consists of a complete virtual piano arranged in a two dimensional space. The simulation can be utilized for training the hand alone (Piano 1), to improve individuated finger movement, or the hand and the arm together (Piano2) to improve individual finger motion in coordination with arm movement. Fractionation was calculated as the difference in the amount of flexion in metacarpophalangeal (MCP) joint between the cued finger and the most flexed non-cued finger. An adaptive algorithm

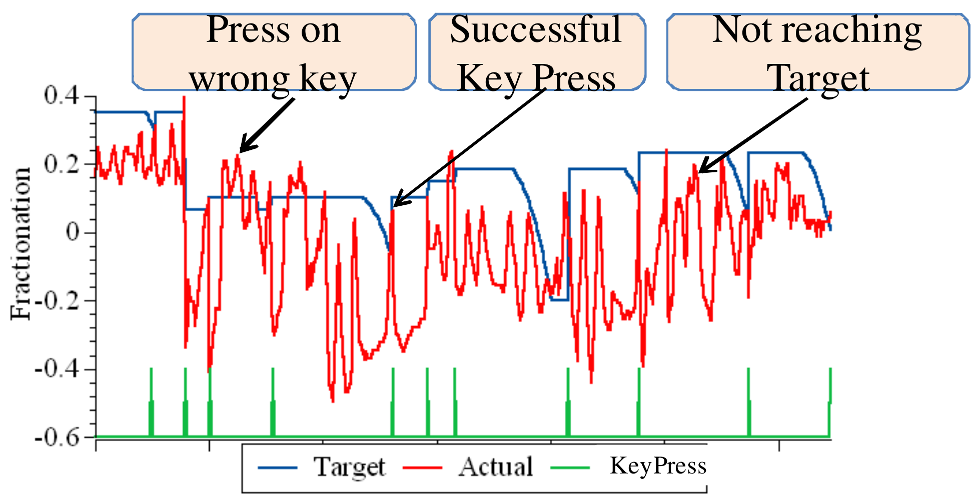


Figure 4.10 Adjustable target fractionation based on actual fractionation.

shapes fractionation requiring more isolated finger flexion to elicit a key press as participants succeed and less stringent requirements if their performance diminishes. Finger kinematics was measured during Piano training for both groups. Movement smoothness was analyzed using normalized integrated jerk. Accuracy denotes the percent of correct key presses.

Figure 4.10 shows an example of variation in the adjustable target fractionation based on individual subject's actual fractionation. Blue line is the target fractionation, red line is actual fractionation and green line indicates when key is successfully pressed. The left box shows the scenario when subject reaches the target fractionation but finger is not aligned with the correct key. The right box shows the scenario when subject fails to reach target fractionation. Initial target fractionation was dynamic throughout the training session and was calculated based on the actual fractionation. If the actual fractional

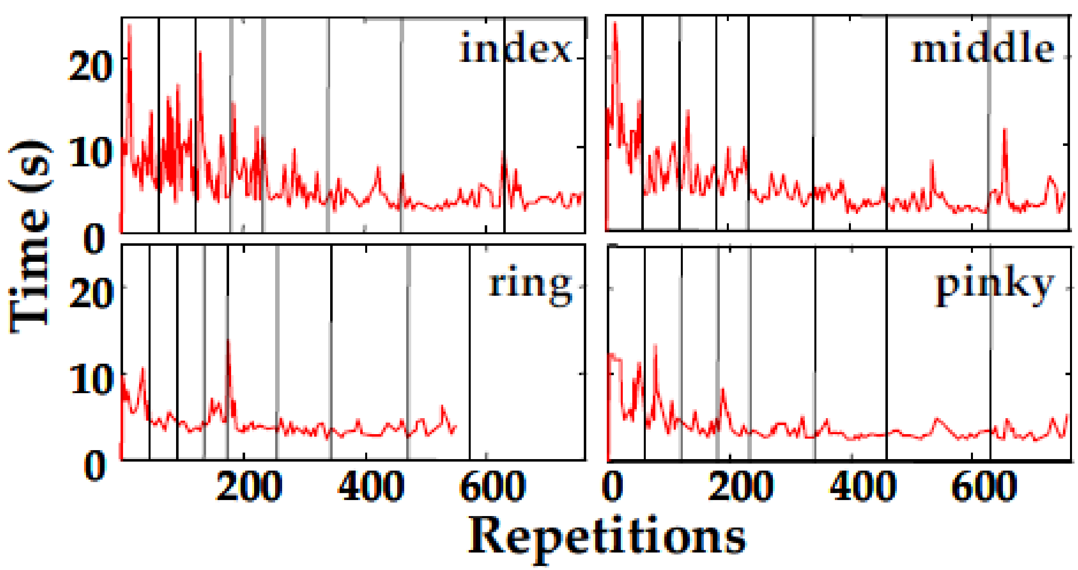


Figure 4.11 Changes in time to approach and press a virtual piano key over the course of 600 to 800 repetitions during the 8 day training intervention are shown for each of the four hemiparetic fingers of a representative subject.

reached 90 percent of target fractionation, the next initial target fractionation increased by eight percent of the previous target fractionation, if not, the next initial target fractionation decreased by ten percent of previous target fractionation.

A total of 20 HAS and 20 HAT subjects completed the piano training. Figure 4.11 demonstrates changes in time to approach and press a virtual piano key over the course of 600 to 800 repetitions for each of the four hemiparetic fingers of a representative subject during the 8 day training intervention. Figure 4.12 indicates the average improvement throughout eight training days. HAS group showed significant improvement in fractionation (47.5%), but not in accuracy and duration. HAT group had significant improvement in both duration (25%) and fractionation (43.2%), but not in duration. It is

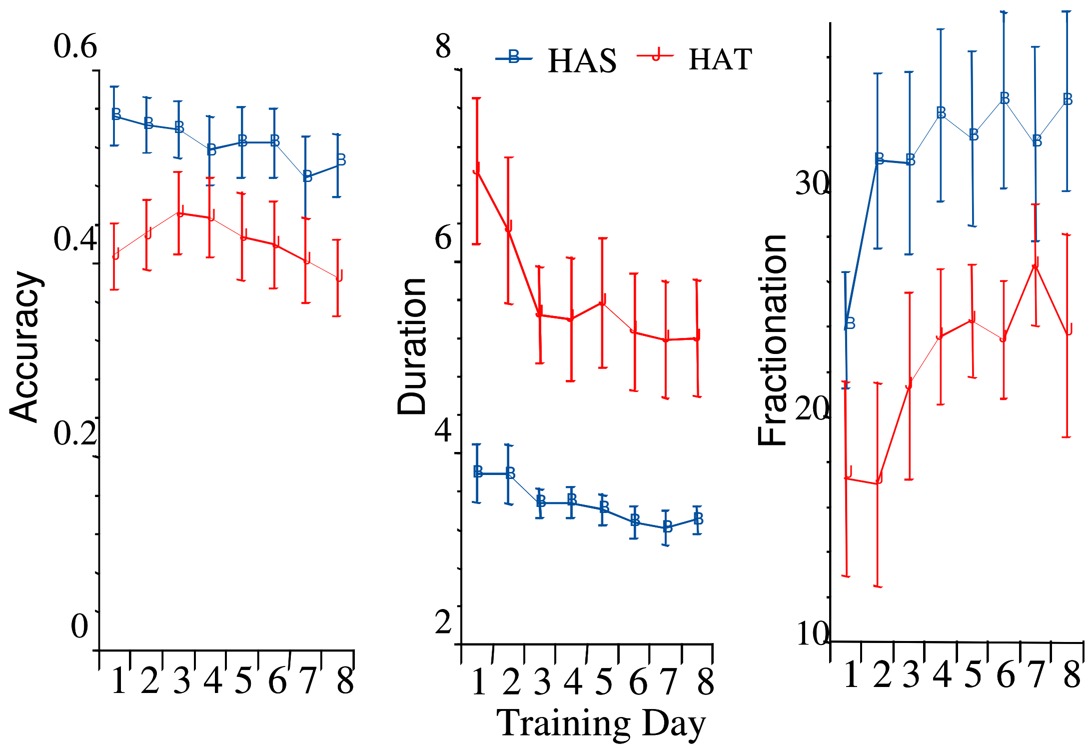


Figure 4.12 Average change on Accuracy, Duration and Fractionation from both HAS and HAT group.

possible that subjects did not demonstrate meaningful changes in accuracy because the virtual piano trainer simulation emphasized increasing the range of individual finger movement and less emphasis on accuracy.

4.3.2 Reach to Grasp Test

12 HAS subjects, 10 HAT subject and 11 control subjects participated in ReachGrasp test. This test can be divided into three sub movement: a reach and grasp, transport and release, and return to the initial resting position. The onset of the movement was designated as being the time at which the 3-dimensional velocity exceeded 3% of the

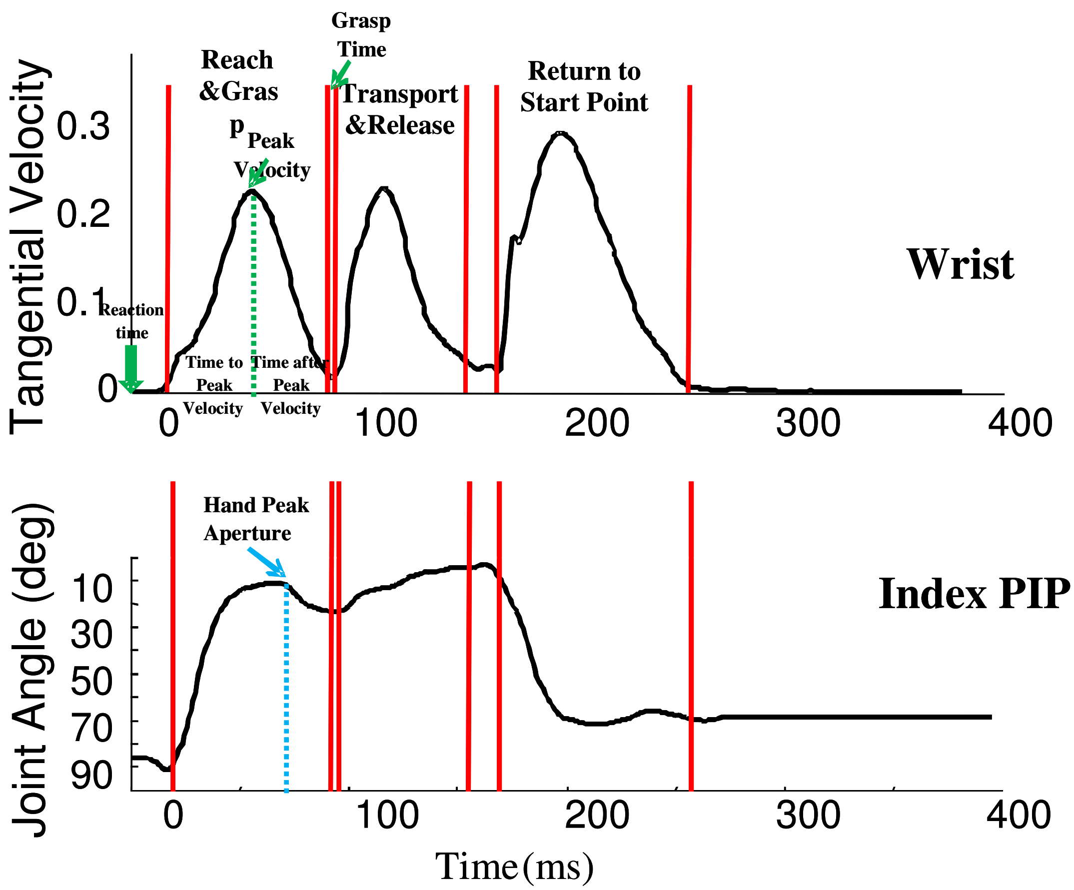


Figure 4.13 An example of a tangential wrist velocity profile of a reaching movement in the ReachGrasp test synchronized with the angular trajectory of the index finger PIP joint.

peak velocity of that sub-movement. The end of the movement was defined as wrist direction turning point. Each sub-movement was processed to calculate Reaction Time, Time to Peak Wrist Velocity, Wrist Peak Velocity, Time to Peak Wrist Deceleration, Percentage Time to Peak Deceleration, Time After Wrist Peak Velocity, Time to Grip Aperture, Time to Peak Grip Aperture, Maximum Grip Aperture and Percentage Time to Peak Grip Aperture.

As shown in Figure 4.13, reaction time was defined as the time between starting signal and onset of the movement. Time to peak velocity (TTPV) was defined as the time between the onset of the movement and the time when subject reached the fastest speed. It was used to analyze patients' ability to coordinate his shoulder and elbow. Time after peak velocity (TAPV) is defined as the time after the subject reached the fastest speed and the time when subject lifted the objects to initiate the object transport movement. It was used to evaluate patients' ability to fine-tune grasp prior to object transport. Hand trajectories of patients performing the entire three-movement sequence are presented to demonstrate changes in his ability to coordinate the shoulder and elbow joints.

Time to Peak Wrist Deceleration was defined as time between onset of the movement and the time when subject reached the deceleration peak. Percentage Time to Peak Deceleration was defined as the time to peak deceleration as a percentage of the movement duration.

Time to Grip Onset was the time between starting signal and onset of fingers opening, which was defined as 5 degree difference from initial finger configuration. Maximum Grip Aperture is the biggest distance between thumb and index finger. Time to Maximum Grip Aperture is the time when thumb and index finger attained the largest three dimensional distances from each other

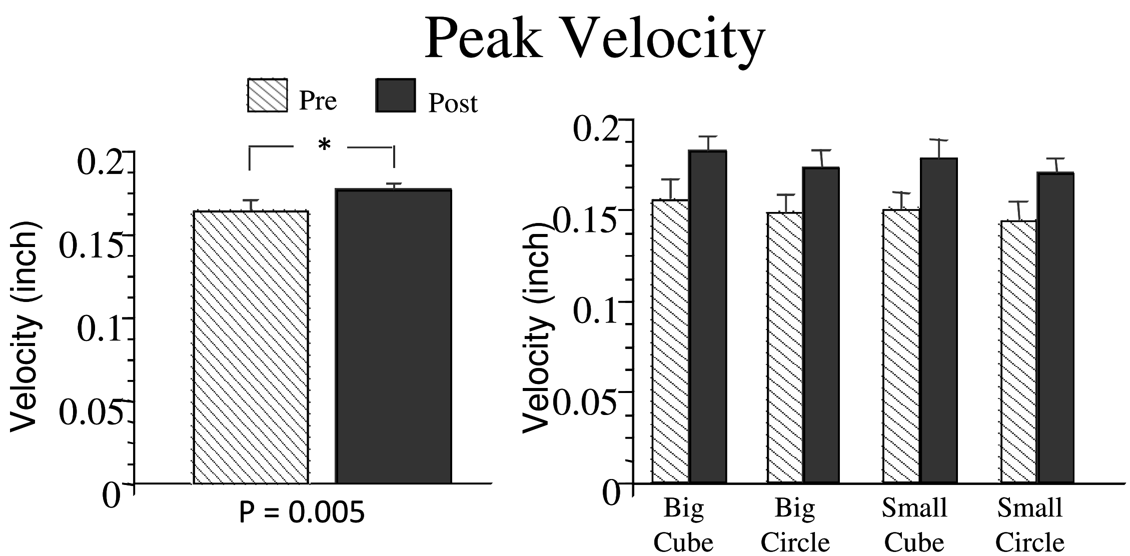


Figure 4.14 Left figure shows that average peak velocity increases across all forty trials significantly after RAVR training. Right figure shows peak velocity changes for each object.

The temporal relationship between transport and grasp was assessed by calculating the correlation between the start of hand opening with the time to peak wrist velocity, and the time to peak grip aperture with time to peak wrist deceleration. Within-group correlation coefficients were calculated for each group. Repeated analysis of variance ANOVA was used to compare the changes in the scores after RAVR training and between groups.

4.3.2.1 HAS and HAT Pre and Post Training Test Statistics Figure 4.14 left panel shows the significant peak velocity increasing from pre-training test to post-training test (pre: mean=0.153 inch/s, SD=0.04; post: mean=0.175 inch/s, SD=0.035; $F(1,20)$ =8.892, p=0.005). Right Figure indicates the peak velocity increase between pre and post training for each object, individual values are listed in Table 4.6.

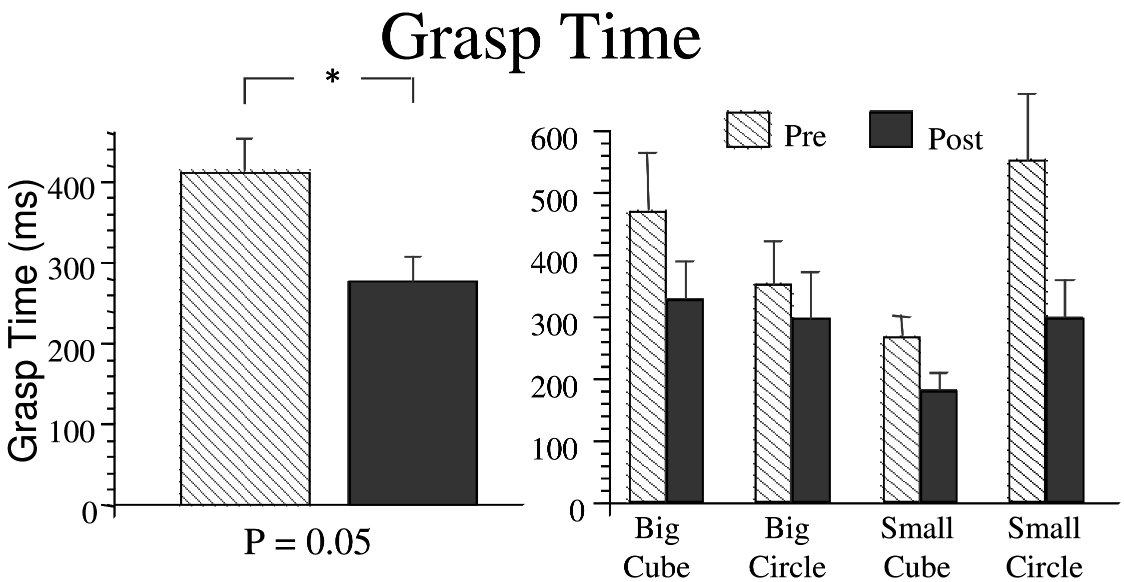


Figure 4.15 Left panel shows grasp time decrease after RAVR training. Right panel shows mean grasp time changes after training for each object.

Grasp time decreased significantly after RAVR training as shown in Figure 4.15 left panel. Right panel shows average grasp time changes after training for each object, individual values are listed in Table4.7.

Table 4.6 Peak Velocity Change in Pre and Post Test

Objects	Pre-Training		Post-Training	
	Mean(inch/s)	SD	Mean(inch/s)	SD
BigCube	0.159	0.044	0.180	0.034
BigCircle	0.152	0.040	0.173	0.036
SmallCube	0.153	0.037	0.178	0.039
SmallCircle	0.148	0.040	0.170	0.033

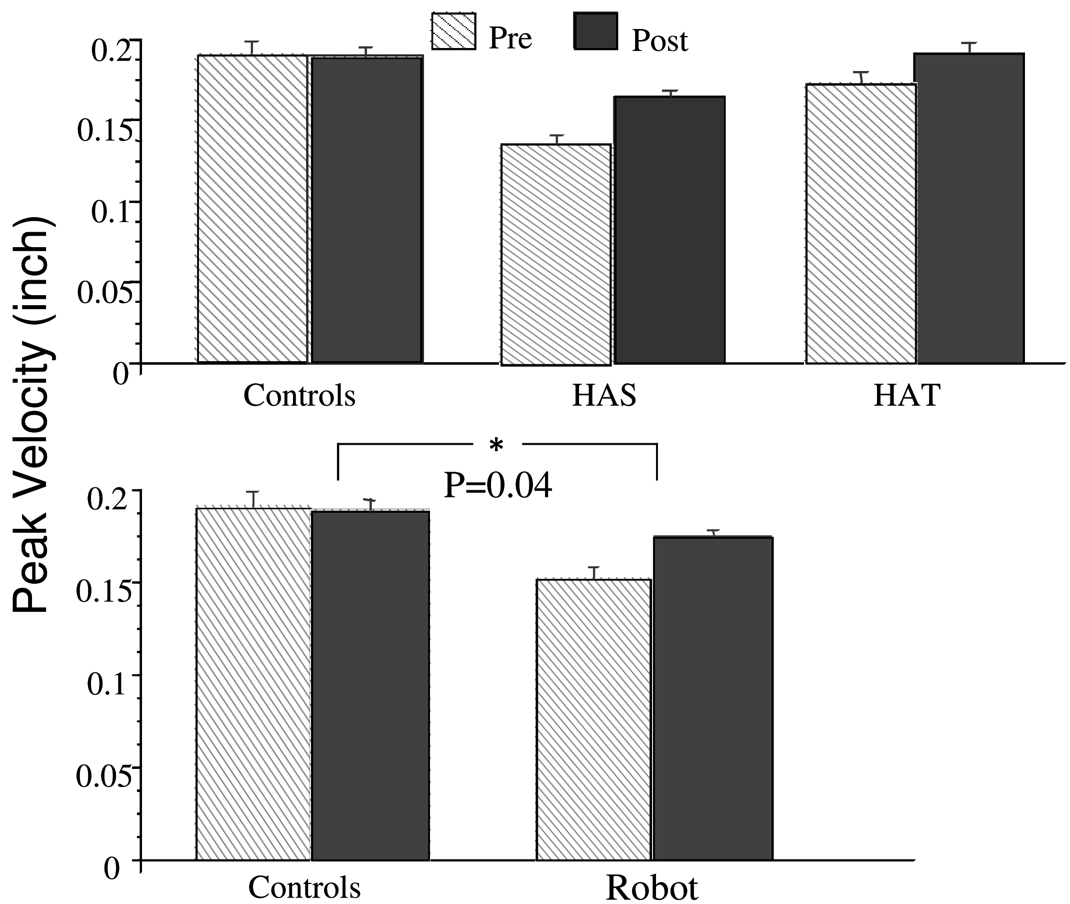


Figure 4.16 Peak velocity comparison between HAS, HAT and Control group.

4.3.2.2 Robot Group and Control Group Statistics To investigate the therapy effectiveness between control group and robot group, HAS and HAT group were combined into Robot group. Repeated measures ANOVA were performed on all kinematics. Three HAT subjects, one HAS subject and one Control subject were excluded from original data as outliers. Reason to exclude those subjects are that they are

Table 4.7 Grasp Time Change in Pre and Post Test

Objects	Pre-Training		Post-Training	
	Mean(ms)	SD	Mean(ms)	SD
BigCube	472.803	381.301	330.161	246.699
BigCircle	353.546	290.172	298.7.3	309.733
SmallCube	269.227	135.704	182.483	114.998
SmallCircle	553.971	435.182	299.693	249.325

not able to perform the post training test well either because of sudden temperature drop cause muscle tone increase, or suffer from ataxia.

ANOVA shows a significant difference in peak velocity between HAS, HAT and

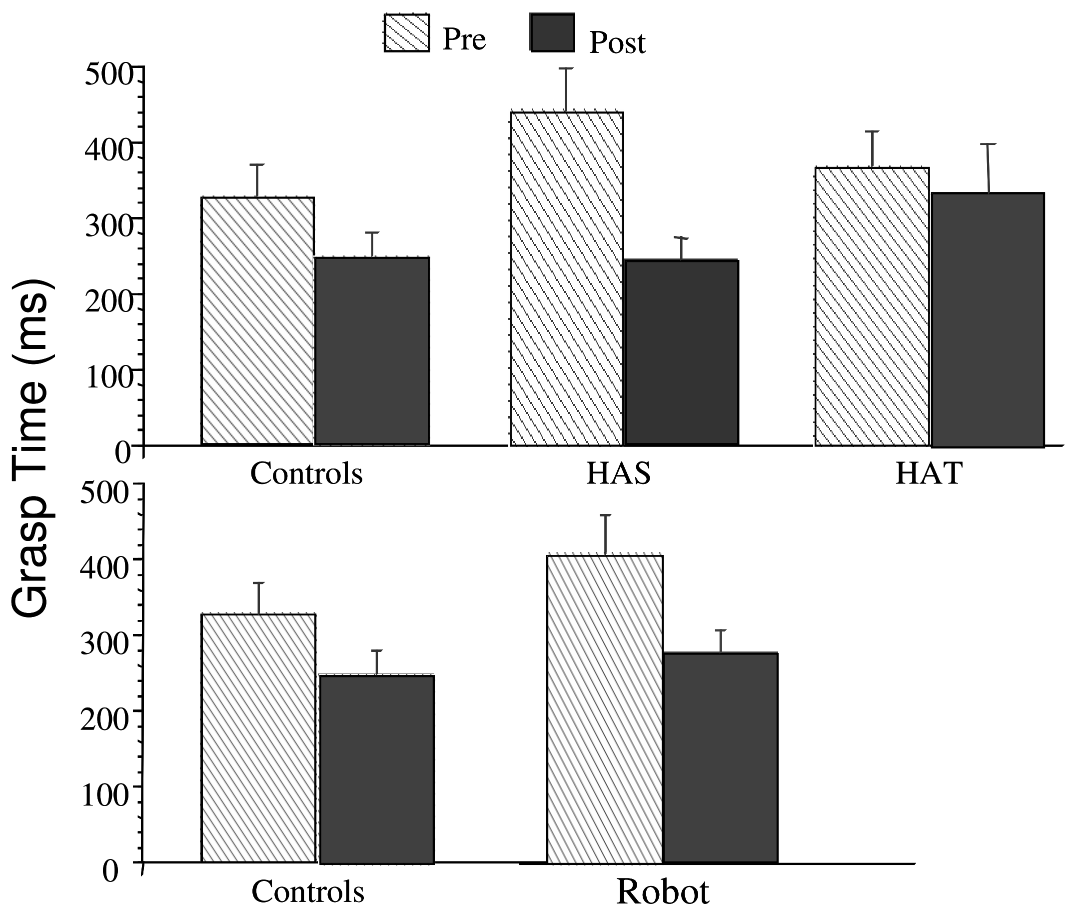


Figure 4.17 Grasp time comparison between HAS, HAT and Control group.

control group (p = 0. 026) . Peak velocity in the Combined HAS and HAT (Robot) group was significantly larger than in the Control group as well (p = 0.018) (Figure 4. 16).

ANOVA shows that there is no significant difference in grasp time between HAS, HAT and control group (p = 0. 11), and between RAVR and Control group as well (p =

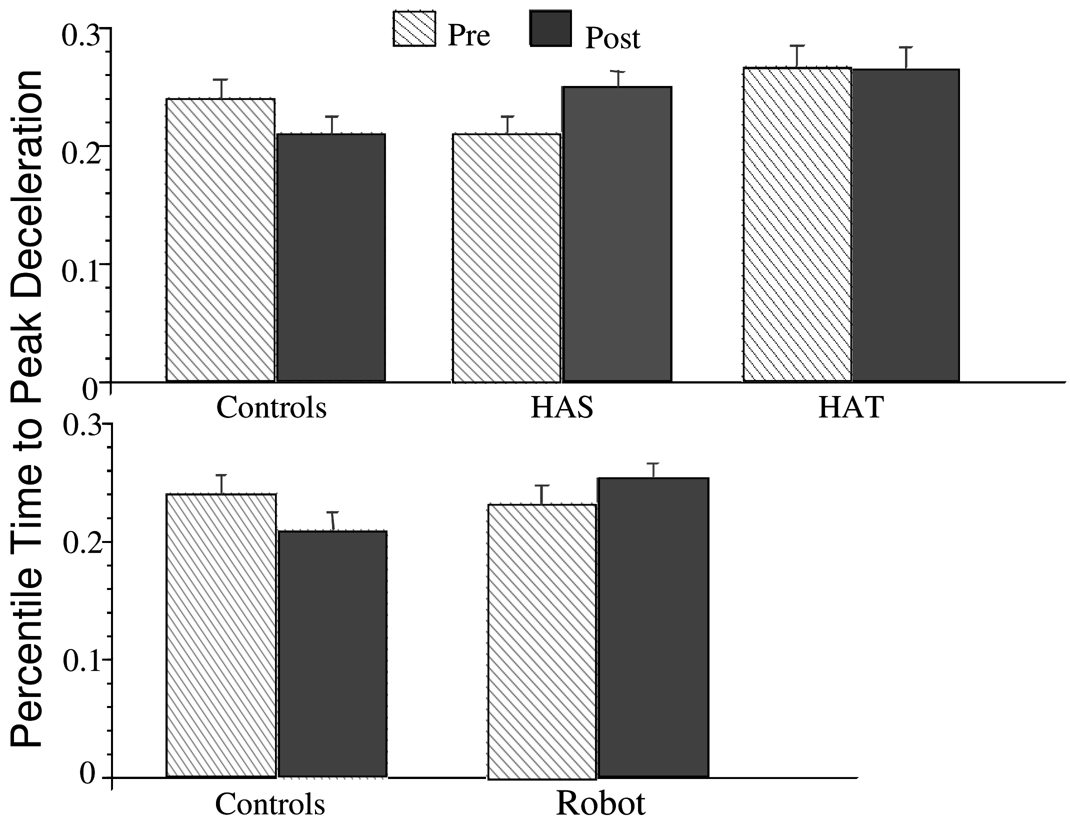


Figure 4.18 Percentile time to peak deceleration comparison between HAS, HAT and Control group.

0.16) (Figure 4. 16). Percentile time to peak deceleration decreased for Control group after training from 24% to 21%, while increased for Robot group from 23% to 25.5%. However, the difference was not significant (Figure 4.18). There was no significant difference between groups found in other Reach to Grasp kinematic measures (please see Appendix E for all statistical results.)

4.3.3 Clinical Outcome Measurements

All 20 HAS subjects, 20 HAT subjects and 12 Control subjects had clinical measurement two weeks and one day before the training and one day after the training. Three HAT subject, one HAS subject were excluded from statistical analysis. Clinical measurements included Wolf Motor Function Test (WMFT), Jebsen Test of Hand Function (JTHF), Nine Hole Peg. Jebsen scores were cut off at 45 seconds to decrease outliers. Only Wolf Motor Function Test and Jebsen Test were used in the statistical analysis because some subjects were not able to perform the Nine Hole Peg Test.

4.3.3.1 Clinical Statistical Analysis Result Control subjects were able to finish WMFT 14.48 seconds faster after training. HAS subjects were 23.6 seconds faster and HAT subjects were 20.75 seconds faster. Each group showed a statistically significant improvement with p = 0.005 for Control group, p = 0.001 for HAS group and p = 0.015 for HAT group. While comparing percent improvements between groups, there was no significant differences observed (Figure 4. 19).

Control subjects were able to finish JTHF 10.61 seconds faster after training. HAS subjects were 16.23 seconds faster and HAT subjects were 31.11 seconds faster. All of these improvements were statistically significant, with p = 0.032 for Control

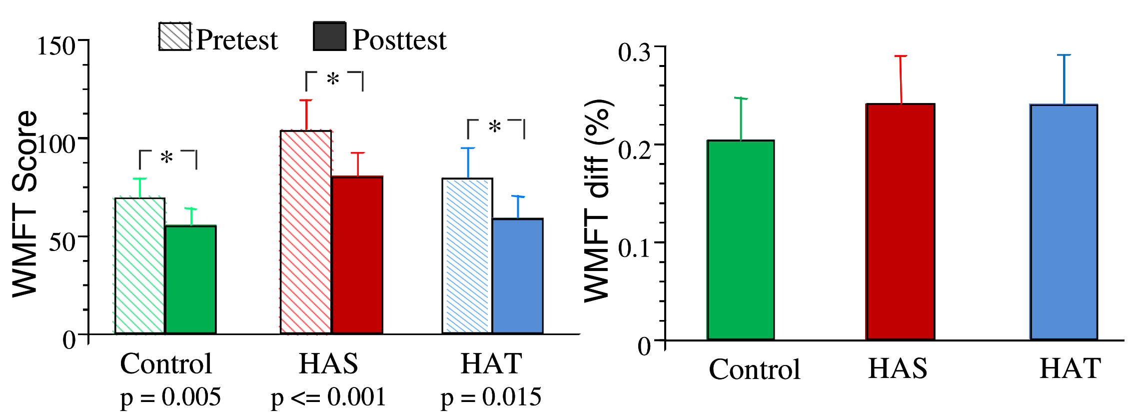


Figure 4.19 Wolf Motor Function Test statistical results.

group, p < 0.001 for both HAS and HAT group. When comparing percent improvements between groups, there was no any significant differences observed (Figure 4. 20).

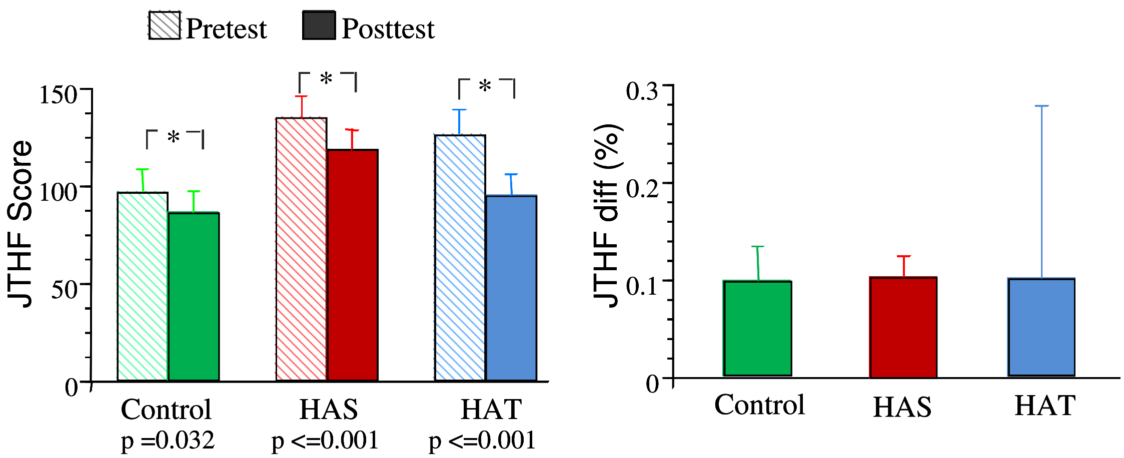


Figure 4.20 Jebsen Test of Hand Function statistical results.

4.4 Conclusions

Both HAS and HAT groups demonstrated meaningful changes in both primary (clinical tests) and secondary (daily kinematics and ReachGrasp Test) outcome measurements. Since Hammer and Piano are two simulations used in both groups, kinematic measurements collected during these simulations were used as secondary outcome measurement to make comparisons across the two groups. Both groups showed significant decreases in duration, path length and trajectory smoothness. In Piano simulation, subjects from both groups were able to improve in movement duration and fractionation while still maintaining the accuracy of key presses. All groups including the control group had improved in some of ReachGrasp measurement variables. They all showed a significant increase in peak velocity and decrease in time after peak velocity. It means that after two weeks of training, subjects were able to move faster, and needed less time to adjust hand shape for grasping. However, they didn't show changes in reaction time, finger peak aperture and finger aperture speed.

Comparisons between HAS and HAT groups did not reveal any differences in the amount of motor function improvement as measured by movement kinematics during training, but the two training methods seem to elicit different patterns of motor learning. HAS training seems to maximize learning more quickly, but overall learning is smaller. This could be due to the greater complexity of the multiple effector HAT tasks.

Comparisons between Robot (HAS and HAT) group and control group showed some differences in the amount of training induced changes in peak velocity and time to peak deceleration (measured as a proportion of the total movement time). After two weeks of training, Robot group increased in peak velocity and time to peak deceleration while control group decreased in both. The time after peak deceleration is the period where feedback is more likely to be used to adjust the goal-directed movement for improved accuracy [100]. Subjects from the control group did not improve their ability to use this feedback quickly and efficiently to successfully lift the object, while subjects who participated in the robotic training needed less time after training for fine tuning their hand shape to the shape of the objects..

CHAPTER 5

STUDY ON CHILDREN WITH CEREBRAL PALSY

5.1 Introduction

Cerebral palsy is the most common cause of physical disability in children, with two to three out of 1000 newborn babies diagnosed per year [101]. It produces non-progressive motor dysfunction, and multi-joint incoordination in both upper and lower extremities. An impaired upper extremity significantly affects self-care activities such as eating, dressing and play [102].

"Massed practice" interventions based on motor learning theories emphasize the repetitive practice of goal oriented tasks designed to address impairments. This treatment approach was initially studied in children with CP by Fetters who found that this approach compared favorably to a traditional neuro-developmental approach [84]. Gordon and colleagues examined a massed practice intervention utilizing both hands to solve movement problems which demonstrated improvements in measurements of assisting hand behaviours and caregiver ratings of bimanual coordination [103]. Constraint induced therapy is another massed approach, which combines structured practice with a therapist and unstructured completion of daily tasks with the participation of the involved extremity enforced by restraining the less impaired extremity [104].

Several technology based approaches to massed practice are being developed. Multiple studies have examined virtual reality interactive computer games with individuals with stroke and children with cerebral palsy. The overall findings support that virtual reality systems enhance upper limb rehabilitation and habilitation with both of these populations. It is suggested that the use of continual massed practice combined with the motivational features built into the interactive virtual reality (VR) games is contributing to this change [49, 105-107]. Other authors cite VR as a method of achieving expanded practice times for children with motor impairments, fulfilling one of the main tenants of massed practice [108-110].

The manipulative ability required to interact with VR systems using hand held controls such as a joystick or computer mouse, exceeds that of many children with CP. Hand-held controllers can also limit the size of the excursion used to interact with a simulation, making them less effective for shoulder training tasks. One method of bypassing this challenge is an approach called video capture. These VR systems utilize cameras to collect position information, allowing participants to use larger body movements to interact with virtual environments (VEs), without hand held controllers [111]. One of the limitations to this approach is the inability to shape or assist desired movement patterns because camera based systems do not allow for physical interactions between the VE and the subject.

Several other authors have attempted to expand the group of persons with CP able to access VR by using robotic systems to interface with simple VEs. Robotic interfaces allow multiple methods to shape movement patterns which include the physical human computer interface, haptically rendered obstacles and global forces such as anti-gravity or damping. Recently, Fasoli and colleagues reported improvements in Quality of Upper Extremity Test and Upper Extremity Fugl-Meyer Assessment scores in a group of 5 to 12 year old children with UE hemiplegia secondary to CP [78]. A similar pilot study by Frascarelli and colleagues [112] utilized guided and unguided movements facilitated by the same robotic system used in the Fasoli and colleagues study. Subjects made statistically significant changes in QUEST, UEFMA as well as the smoothness and speed of the trajectories measured during reaching training. These studies both utilize repetitive, two dimensional reaching tasks.

The pilot study was designed to establish the feasibility of the NJIT-RAVR system for use by young children with mild to moderate hemiplegia secondary to CP. The system was redesigned and modified to be sufficiently adaptible to address the therapeutic goals identified by subjects' therapy team, and to provide variety of sensory stimulations in each virtual environment simulation to span children's attention. Different visual and auditory presentations were implemented in simulations to accommodate varying levels of processing ability [43], in order to establish that the combination of robotic facilitation of two and three dimensional movements with complex game-like virtual simulations can accomplish the repetition, attention and meaningfulness required for effective massed practice. In addition authors attempted to demonstrate that nine hours of RAVR training may contribute to measurable improvements in motor function in children with UE hemiplegia secondary to CP.

5.2 Methods

5.2.1 Subjects and Training Paradigm

Criteria for inclusion were 1) Diagnosis of hemiplegia secondary to CP 2) Residual but impaired active movement of the shoulder, elbow and wrist 3) The ability to tolerate passive shoulder flexion to shoulder level. The criterion for exclusion was a history of visually evoked seizures. Parental consent and child assent was established for each participating child. The entire protocol was approved by the Internal Review Board of the

New Jersey Institute of Technology. Provisions of the International Code of Medical Ethics of the World Medical Association were satisfied throughout the study. Two different groups of children interacted with the RAVR system during the study period. Three subjects formed a Robot group , and four subjects performed a combined RAVR and CIMT program as a part of a therapeutic camp experience (CIMT + RAVR). Subjects were selected from a convenience sample of children between the ages of five to 18 years of age who had formerly, or were currently receiving occupational therapy at Children's Specialized Hospital. All seven participants used the RAVR System for one hour, 3 days a week for three weeks. Subjects performed four sets of ten reaches utilizing the Bubble Explosion simulation to initiate each session for performance testing purposes. The subjects played a combination of three or four of the other simulations depending on their therapeutic goals, tolerances and preferences for the remainder of the sixty minute sessions.

5.2.2 Robot Group

Nine children (average age =10.1) were trained with a goal of refining simulations, positioning and training techniques, to address the therapeutic goals specific to children with CP. Subjects' characteristics are listed in Table 5.1. Initially, these subjects performed their training without trunk restraint. The Occupational Therapists noted that subjects were utilizing compensatory movements of the trunk to complete shoulder and elbow movements. This is consistent with experimental observations made by Levin and colleagues [113]. A harness system (Leckey Seating System) was applied to decrease trunk rotation and lateral flexion, resulting in an increase in shoulder and elbow movement [114]. The height of the Leckey Chair was oriented in relation to the Haptic

Master in order to obtain an initial position of 90 degrees of elbow flexion with humerus resting against the participant's trunk.

Table 5.1 Cerebral Palsy Subjects' Characteristics

Subject	Age	Gender	Lesion side
Robot1	15	M	Left
Robot 2	10	M	Right
Robot 3	9	M	Right
Robot 4	7	F	Left
Robot 5	10	M	Right
Robot 6	9	M	Right
Robot 7	11	M	Left
Robot 8	9	M	Left
Robot 9	11	M	Right
Combined1	5	F	Left
Combined2	6	F	Right
Combined3	12	F	Left
Combined4	11	M	Left

Subjects initially performed the HammerHM task using a combination of pronation and supination with shoulder flexion and elbow extension. This proved to be extremely difficult for both subjects and did not elicit supination movements which were the primary goal of this simulation. Therapists and engineers programmed the RAVR system to limit pronation and eliminate elbow flexion and extension, utilizing only supination movements to interact with the simulation. In addition, a forearm based splint that controlled wrist flexion and extension as well as radial and ulnar deviation, was attached to the robot gimbal to emphasize supination movements as well.

5.2.3 Combined Group (CIMT + Robot)

The second group was a similar sample of three girls and one boy (age 5,6,12 and 11 respectively, Table 5.1) with upper extremity hemiplegia secondary to CP that performed RAVR training one hour, three days a week for the duration of a three week camp as part of an intensive training program that also incorporated a total of six hours of intervention including CIMT and intensive bimanual therapeutic interventions. CIMT consisted of participants wearing a light weight constraint cast on their noninvolved arm for six hours a day for three weeks except for during individual sessions of 30 or 60 minutes per day and during the RAVR training.

5.2.4 Positioning and Splinting

Subjects' extremities were supported in volar forearm or hand based positional splints. Splints were secured to the ring gimbal attachment of the RAVR which enabled shoulder and elbow movements in addition to forearm and wrist movements during game completion. Therapists determined the use of the forearm based splint when the subject

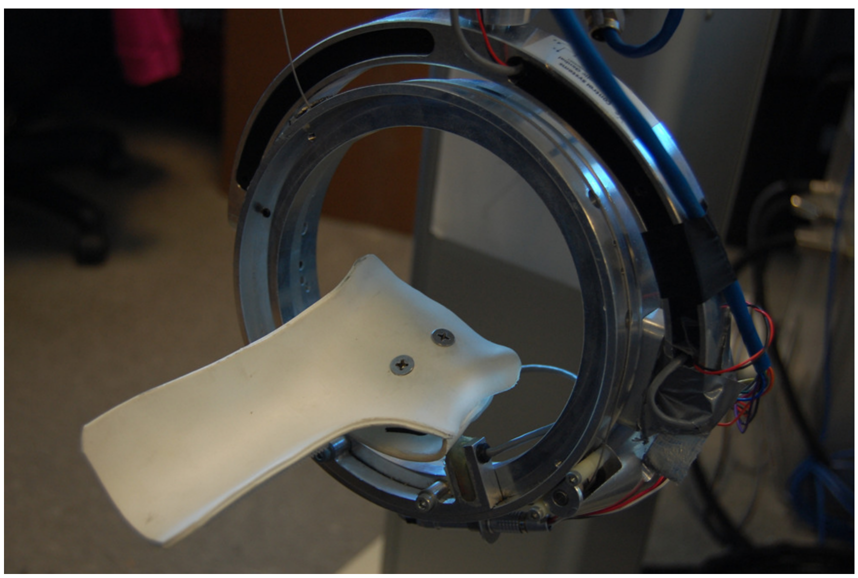


Figure 5.1 Customized splint was used to limit wrist movement.

demonstrated poor distal control or limited wrist movement (Figure 5.1). During completion of haptic master training subjects were secured in a Leckey chair system (Leckey USA) with use of trunk supports, chest vests and foot supports.

5.2.5 Statistical Analyses

Preliminary inspection of the results confirmed normal distribution of the Melbourne test scores and of the kinematic data collected by the robot. Statistical significance for pre to post training changes in Melbourne scores were evaluated using paired, one tailed t-tests. Analysis of variance (ANOVA) with repeated measures factors Time (Pre, Post) and Item (Forward Reach, Sideways Reach, Hand to Mouth and Down) were calculated for the

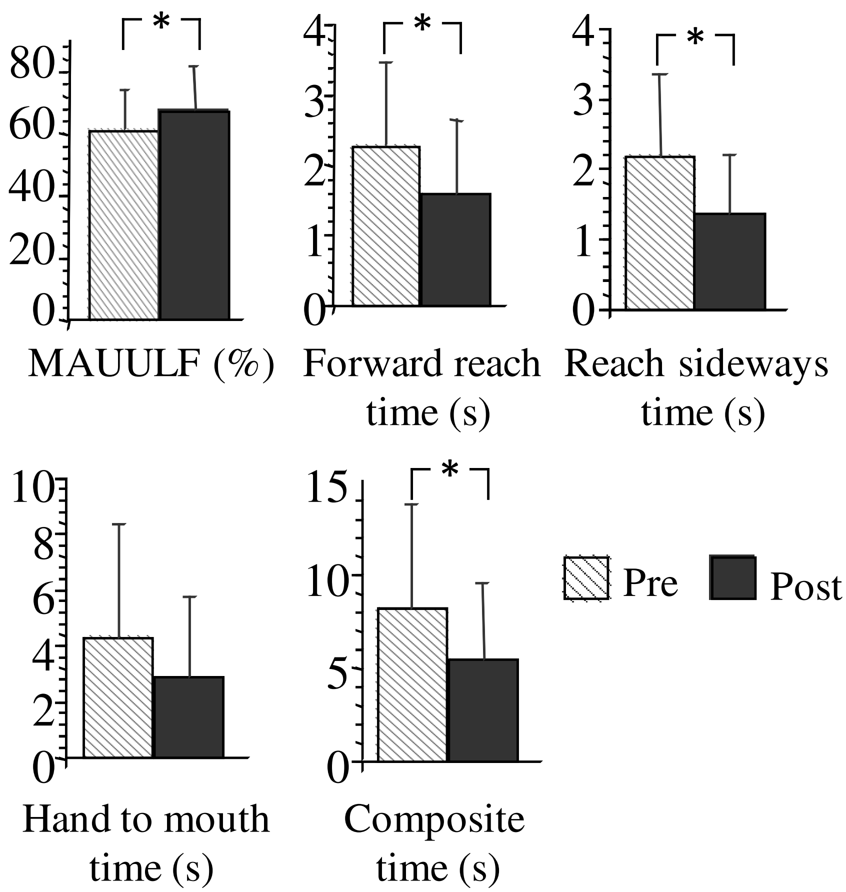


Figure 5.2 Melbourne test and 3 timed Melbourne sub-test.

three timed subtests of the Melbourne. Statistical significance for pre to post test changes were evaluated using paired, one tailed t-tests. Results were considered as statistically significant at P< 0.05. Effect sizes in this paper were calculated by dividing the mean of the difference in the pre and post-tests by the standard deviation of the pre-test scores in order to allow author to use the rating scale developed by Cohen [115, 116] and facilitate comparisons to controlled studies in the pediatric rehabilitation literature. Alternative methods for calculating effect sizes for repeated measures design [117] would yield larger effect sizes.

5.3 Results

5.3.5 Clinical Measurements

Table in Appendix F summarizes Melbourne data which are scored and reported as percentages of the maximum possible score, for the nine subjects. The children performing the combined CIMT + RAVR training demonstrated similar mean improvement on the Melbourne score compared to the RAVR subjects (6.5 and 6.2, respectively). Two children making clinically significant changes in Melbourne score (> 8.9) were in the combined CIMT + RAVR training group and one in the Robot group. When analyzed as a thirteen subjects group, pre to post test change ranged from -2.6 to 12.3. The group as a whole demonstrated a mean change of 5.2 which was statistically significant ($F(1,12) = 19.157$, $p = 0.0009$). Table in appendix F also summarizes performance on the three timed items of the Melbourne. The average changes accomplished by the Robot group were 0.8, 0.8 and 1.2 seconds; and the average changes by CIMT + Robot group were 0.35, 0.9 and 1.7 seconds for these items. Statistical comparisons between the treatment groups for individual items were not significant. Analyzed 13 subjects as a single group, repeated measures ANOVA with factors Time

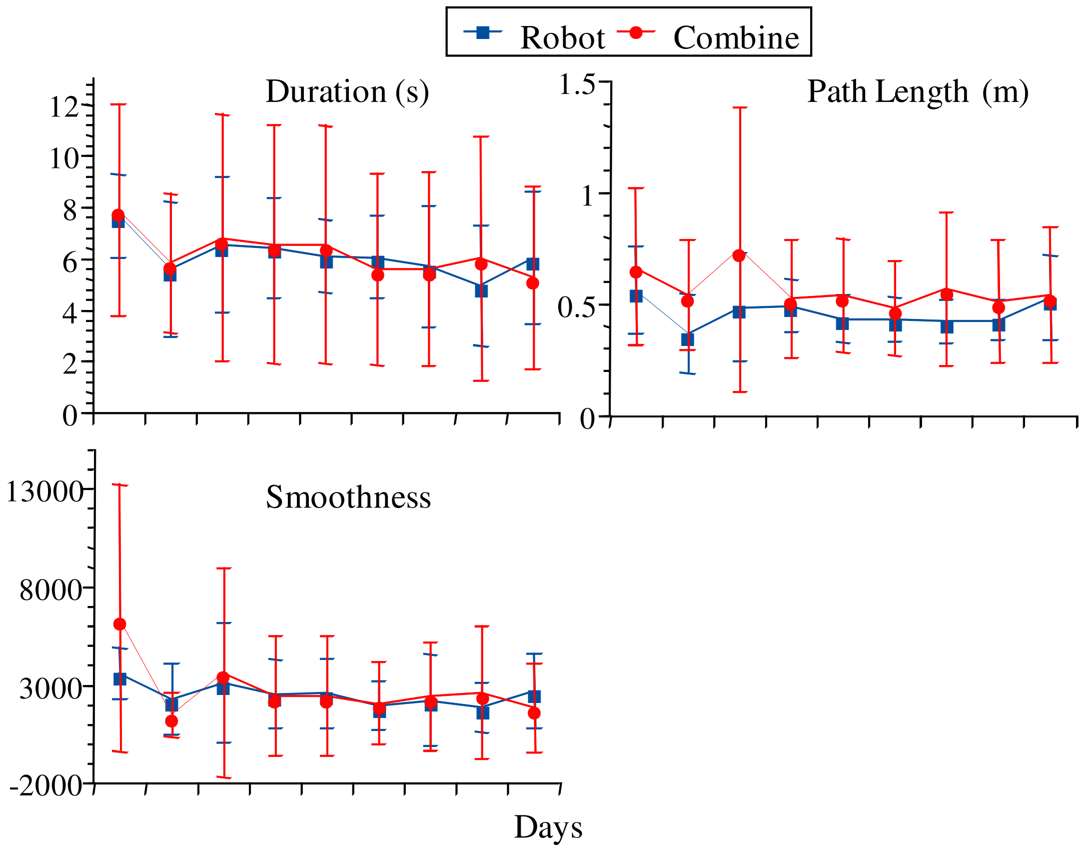


Figure 5.3 Duration, Path Length and smoothness change averaged across subjects from ReachTouch activity.

(Pre, Post) and Item (Forward Reach, Sideways Reach, Hand to Mouth and Down) was performed. There were statistically significant changes in Forward Reach, Reach sideways and Composite, but not in Hand to mouth as shown in Figure 5.2.

The table in appendix G describes changes in active range of motion from pre to post testing for the three Outpatient / RAVR training subjects and the four CIMT + RAVR training subjects. As a group, the children improved an average of 13.2 degrees in shoulder flexion, 8.2 degrees in shoulder abduction, 6.7 degrees in elbow extension, 6.1 degrees of supination and 10 degrees of wrist extension. The changes in shoulder flexion ($F(1,10) = 7.945$, $p=0.018$) were statistically significant. The table in appendix G also describes changes in the Functional Levels of Hemiplegia test. All three Outpatient /

Robot group subjects improved one level. Two of the CIMT + Robot group children also improved, one a single level and one made a three level improvement.

5.3.2 Movement Kinematics

Table 5. 2 ReachTouch Kinematics Results

Subjects	Duration (s)		Path Length (m)		Smoothness	
	pre	post	pre	post	pre	post
Robot 1	5.871	3.914	0.256	0.245	1186.934	602.211
Robot 2	9.771	9.133	0.753	0.651	4792.931	3781.895
Robot 3	9.449	9.360	0.900	0.738	3379.099	3412.403
Robot 4	8.348	2.754	0.698	0.249	3124.903	191.417
Robot 5	5.0688	3.4169	0.5362	0.4801	1278.1734	810.9347
Robot 6	8.0530	6.6867	0.3665	0.5237	4136.6663	2255.6314
Robot 7	6.8731	5.3033	0.3797	0.4406	2634.7592	1797.7723
Robot 8	8.7841	8.8713	0.4566	0.8038	4337.6427	6235.6265
Robot 9	6.8552	4.9094	0.4322	0.3403	5249.2272	3088.9958
Combined 1	7.9867	3.3233	0.4965	0.3668	2942.9474	490.6853
Combined 2	2.6093	1.9740	0.2993	0.2370	294.0007	132.5179
Combined 3	12.7240	10.0195	1.1054	0.9268	6570.8695	5121.2070
Combined 4	8.2770	5.7680	0.7691	0.6356	15824.5910	1690.1207

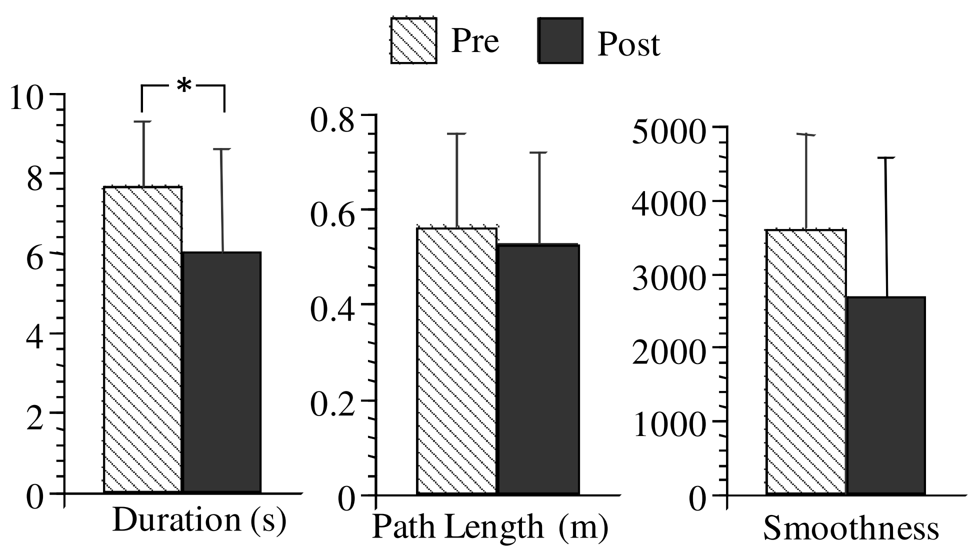


Figure 5.4 ReachTouch pre-post kinematics from the Robot group.

All subjects from Robot and combine group did ReachTouch activity each day. Only 5 Robot subjects did Hammer activity because of hardware issues. Figure 5.3 shows the daily duration, Path Length and smoothness change averaged across subjects from ReachTouch activity. Blue line is Robot group and red line is Combined group. Subjects from Robot group demonstrated significant improvements in Duration (First day Mean (SD) = 7.633 (1.477), Last day Mean (SD) = 5.900 (2.544); $F(8,1) = 8.552$, $p=0.0192$), but not significant improvement in Path Length (First day Mean (SD) = 0.538 (0.195), Last day Mean (SD) = 0.511 (0.200); $F(8,1) = 0.215$, $p=0.6551$), or Smoothness (First day Mean (SD) = 3448.639 (1290.271), Last day Mean (SD) = 2541.826 (1994.049); $F(8,1) = 3.576$, $p=0.0953$) (Figure 5.4). Subjects from the Combined group demonstrated significant improvement in Duration (First day Mean (SD) = 7.899 (4.140),

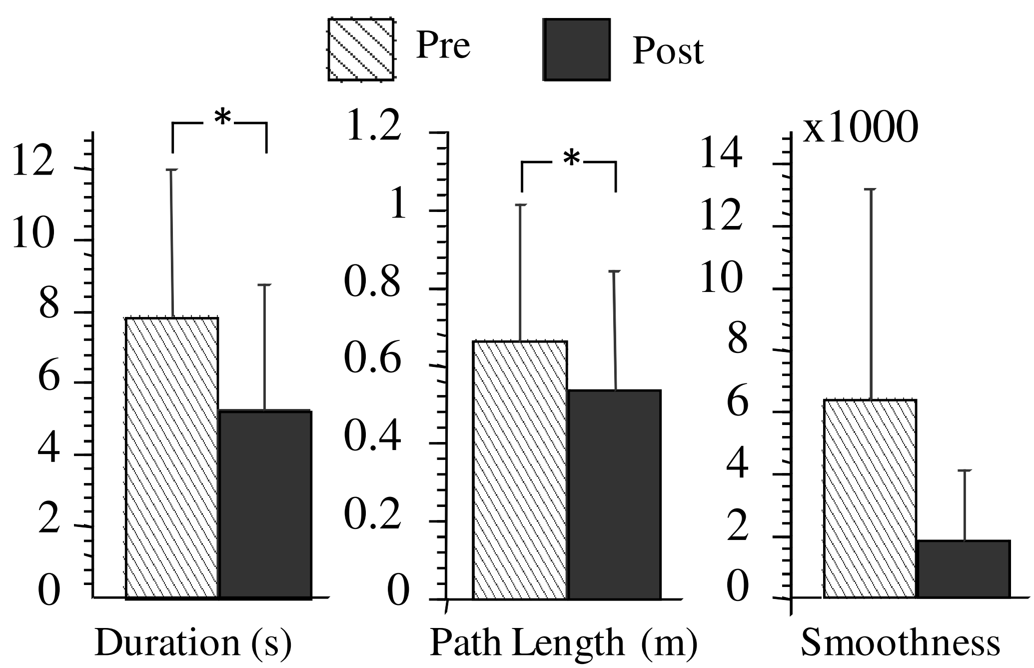


Figure 5.5 ReachTouch pre-post kinematics from the Combine group.

Last day Mean (SD) = 5.271(3.534); $F(8,1) = 10.190$, $p=0.0496$), and Path Length (First day Mean (SD) = 0.668 (0.350), Last day Mean (SD) = 0.542 (0.306); $F(8,1) = 27.644$, p=0.0134), but not significant improvement in Smoothness (First day Mean (SD) = 6408.102 (6784.450), Last day Mean (SD) = 1858.633 (2274.756); F(8,1) = 1.985, p=0.2536) (Figure 5.5). Table 5.2 lists each subject's ReachTouch kinematics from the first day and last day of training.

Hammer kinematics included duration which was calculated as the total time to complete one peg; peak angle that is the recoded as the biggest wrist rotation angle; peak velocity that indicates how fast subject rotate; and rotation smoothness that is derived

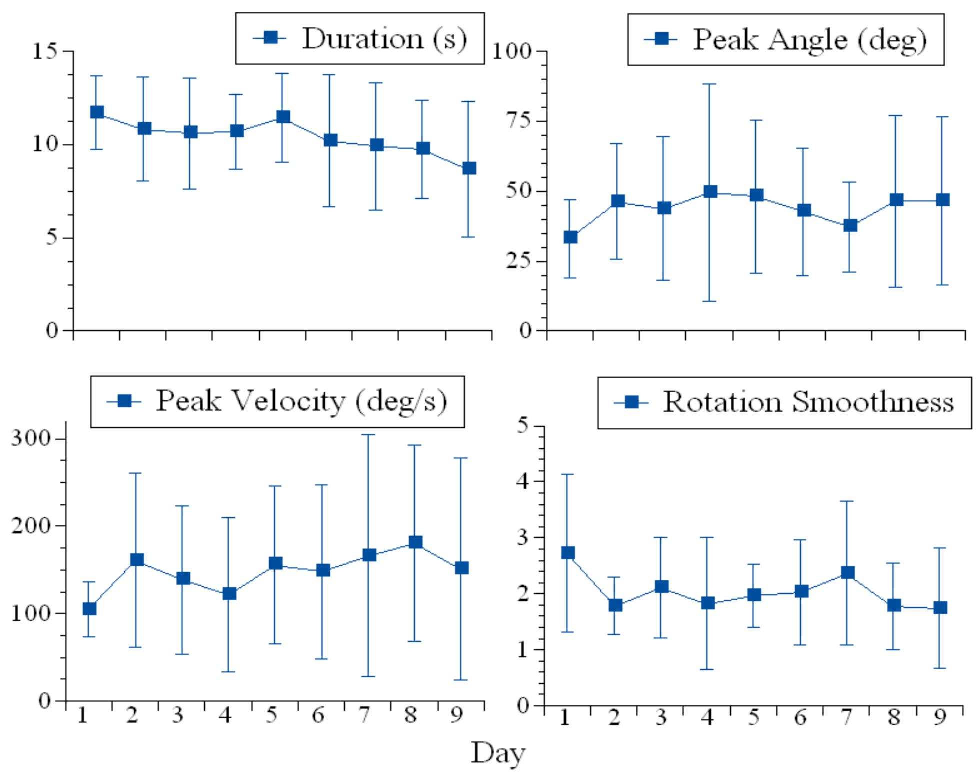


Figure 5.6 Duration, peak angle, peak velocity and rotation smoothness change averaged across subjects from the Hammer activity.

from angular velocity. Figure 5.6 shows the daily kinematics change average across subjects. Compared between the first day and last of training, subjects showed improvement in duration (first day mean (SD) =11.706 (1.991), last day mean (SD) =

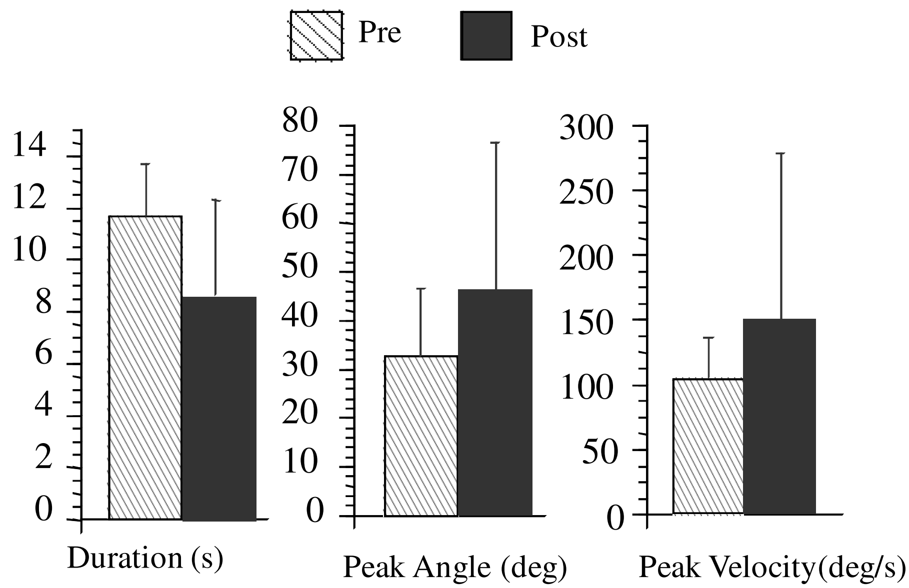


Figure 5.7 Hammer pre-post kinematics from the Robot group.

8.659 (3.641)), peak angle (first day mean (SD) = 32.996 (13.799), last day mean (SD) = 46.587 (30.099)), peak velocity (first day mean (SD) = 104.834 (30.918), last day mean (SD) = 150.862 (127.212)), and rotation smoothness (first day mean (SD) = 2.717 (1.411), last day mean (SD) = 1.743 (1.078)) (Figure 5.7). Table 5.3 lists each subject's Hammer kinematics from the first day and last day of training.

Table 5.3 Hammer Kinematics Results

Subjects	Duration		Peak Angle		Peak Velocity		Rot. Smoothness	
	pre	post	pre	post	pre	post	pre	post
Robot 3	8.166	6.169	55.098	41.868	285.691	225.734	2.127	1.475
Robot 4	13.65	10.542	23.911	25.708	87.150	115.697	4.067	1.992
Robot 5	9.383	11.647	48.339	48.623	137.938	146.510	2.147	3.333
Robot 6	10.744	11.911	19.055	11.267	71.240	62.3471	3.654	1.164
Robot 7	13.046	4.9085	40.676	84.586	123.02	319.718	1	1

5.3.3 Response to Simulations

As a nine subject group, the children averaged a total of 24 minutes of time on task during the sixty minute training sessions. Table 5.4 summarizes the average time subjects participated in each simulation when it was utilized, and reports the relative frequencies of decreased attention or signs of fatigue demonstrated by subjects during training. There was no consistent correlation between training time, and fatigue or attention issues.

Table 5.4 Participation Time, Attention and Fatigue Issue Frequencies

	FallingObjects	ReachTouch	CarRace	Hammer	Cups
Time (SD), sec	6.62 (3.2)	8.49 (3.48)	5.88 (3.37)	3.93 (2.44)	5.47 (2.42)
Attention	11/56	8/81	0/70	8/18	0/27
Fatigue	18/56	29/81	22/70	18/18	14/27

5.4 Conclusions

This dissertation describes the first system combining complex, haptically rendered, three dimensional virtual environments and robotics to train the upper extremity of children with CP. All of the subjects in this study utilized the RAVR system without adverse reactions or complications. No seizure activity or symptoms associated with cyber sickness were noted [118]. NJIT RAVR system which was initially designed to accommodate persons with strokes [77, 119] was easily re-fitted and modified to allow for interaction with children. During the first pilot study, a need was identified to increase emphasis on active supination. This was accomplished by decreasing the complexity of the HammerHM simulation and using longer splints to interface between robot and participants. This resulted in significant increases in active supination, achieved by subjects during training, which carried over into improvements in active range of motion during post-testing.

The Melbourne Assessment of Unilateral Upper Limb Function Test, the main functional outcome measure used in this study utilizes observational ratings of motor performance and motor control. This is common to other standardized measurements of upper extremity function for children. To extend the observational approach, three activities from the Melbourne were timed. When pooling these times as is done to interpret other batteries designed for adults, the group of nine subjects demonstrated statistically significant improvement with a moderate effect size (d= 0.65). Author feels that development of a more comprehensive battery of timed, standardized upper extremity movements would significantly contribute to the pediatric rehabilitation literature.

To test for improvements in distal function, two tests were incorporated to test the finger strength, grip and pinch dynamometry. As would be expected, the combine group made the largest improvements in grip and pinch strength, most likely due to the extensive distal effector interactions involved in the combine protocol. Interestingly, the Robot groups also made positive changes. Similar improvements of smaller magnitude in distal function in response to proximal upper extremity robotic training have been described in the adult stroke literature [120].

Average time on task for the sixty minute sessions was approximately 24 minutes as measured by the computer system, for the children participating in this study. The 24 minutes described exceeds the time on task reported in the adult stroke literature for treatments of comparable length [121]. A similar study quantifying participation intensities during traditional outpatient or inpatient rehabilitation activities in a population of children with CP is indicated to establish the effectiveness of technologies designed to enhance rehabilitation experiences.

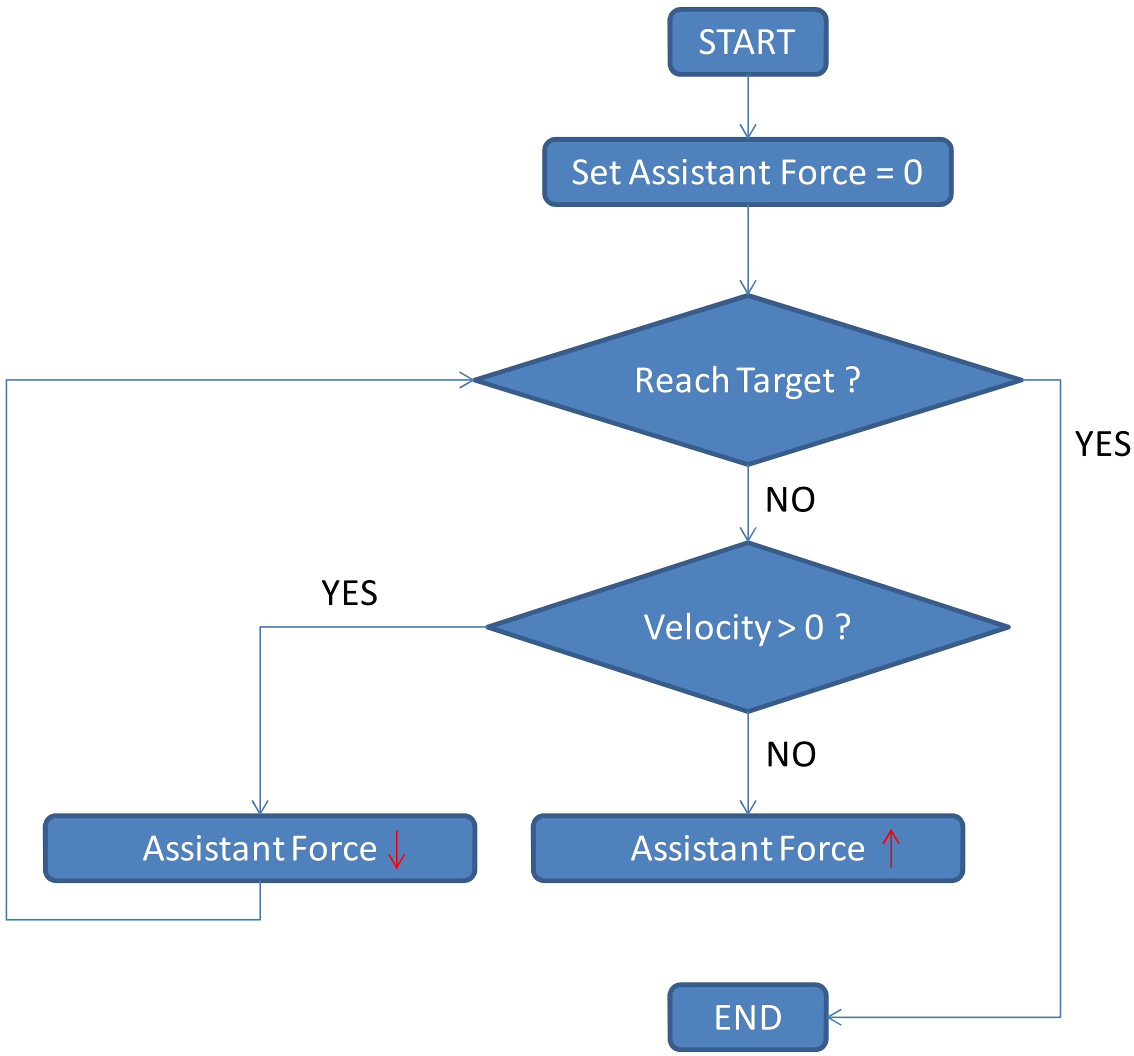
Two specific aspects of training support the RAVR systems ability to affect impairment level change. It is interesting to note that two children with significantly impaired active supination range of motion, a common impairment for children with hemiplegia secondary to CP [32], made large improvements in this construct. The RAVR is unique as a robotic system specifically designed to train this movement in persons with hemiplegia. The nine subjects made a significant improvement in active shoulder flexion. Arm elevation accomplished with shoulder and elbow musculature was another construct stressed during the RAVR training trials described.

The children participating in this trial demonstrated improved performance by these effectors across measurements of AROM, motor function, kinematics and motor control. While subjects' responses to the games varied, they performed each simulation while maintaining attention sufficient to improve in both robotic task performance and improve in measures of motor function. Author feels that this approach to training has demonstrated measurable benefit with minimal complications, warranting further examination and discussion.

APPENDIX A

REACH AND TOUCH ALGORITHM FLOW CHART

The following is a flow chart of the adaptive algorithm used in ReachTouch simulation to control the assistive force.



APPENDIX B

CODE SPECIFICATION FOR REACH TOUCH ALGORITHM

Appendix G is the code specification used in ReachTouch algorithm to control the assistive force.

```
void EnableAssistant()
{
        double ConForce[3];
        double TempVel;
        double TempForce;
        double Deviation;
        double TempSpring[3];
        double TempPosi[3];
        double TempAngle;
        CVertex TempIdeal;
        CVertex TempDir;

        CVertex X(1,0,0);
        CVertex Y(0,1,0);
        CVertex Z(0,0,1);

        CVertex InitPoint(0.12,0,(CenterPos[2]-caBottom));

                if ((StartPlay)&& (SpaceButtom))
                {
                        pHapticMaster->SetForceGetInfo(Force, &MyBuffer);

                        CVertex
                ActPosition((MyBuffer.InfoBlock[0]).Info[0],(MyBuffer.InfoBlock[0]).Info[1],(MyBuffer.InfoBlock[0]).Info[2]);
                        CVertex
                ActVerlocity((MyBuffer.InfoBlock[1]).Info[0],(MyBuffer.InfoBlock[1]).Info[1],(MyBuffer.InfoBlock[1]).Info[2]);
                        CVertex
                ActForce((MyBuffer.InfoBlock[2]).Info[0],(MyBuffer.InfoBlock[2]).Info[1],(MyBuffer.InfoBlock[2]).Info[2]);

                        if ((Vconstrain)&& (elapsed_time>=3)&& (elapsed_time!=Pre_time))
                        {
                                Pre_time=elapsed_time;
                                TempDir=SphereCenter[CurrentBall]-ActPosition;
                                TempVel=TempDir.Dot(ActVerlocity)/TempDir.Length();
                                TempForce=TempDir.Dot(ActForce)/TempDir.Length();

                                if ((TempVel<=AverageV[CurrentBall])&&(TempForce<=0))
                                {
                                        // adjust the assistant spring stiffness
                                        if (AssisSpring< K)
                                                AssisSpring = AssisSpring+20;
                                        pAssisSpring->SetParameter(FCSPRM_SPRINGSTIFFNESS,AssisSpring);
                                        pAssisSpring->Enable();
                                }
                                else
                                {
                                        if (AssisSpring> 0)
```

```
                              AssisSpring = AssisSpring-5;
                        pAssisSpring->SetParameter(FCSPRM_SPRINGSTIFFNESS,AssisSpring);

                }
        }

        if ((Rconstrain)&&((PreP_time-CurP_time)>=10))
        {
                CurP_time=PreP_time;
                TempDir=ActPosition-InitPoint;
                TempIdeal=SphereCenter[CurrentBall]-InitPoint;
                TempAngle=TempDir.Dot(TempIdeal)/(TempDir.Length()*TempIdeal.Length());
                Deviation=TempDir.Length()*sin(acos(TempAngle));

                if (Deviation>Range)
                {

        TempSpring[0]=TempDir.Length()*TempAngle*TempIdeal.Dot(X)/TempIdeal.Length()+InitPoint.m_dCoords[0];

        TempSpring[1]=TempDir.Length()*TempAngle*TempIdeal.Dot(Y)/TempIdeal.Length()+InitPoint.m_dCoords[1];

        TempSpring[2]=TempDir.Length()*TempAngle*TempIdeal.Dot(Z)/TempIdeal.Length()+InitPoint.m_dCoords[2];
                        pRangeSpring->SetParameter(FCSPRM_POSITION,TempSpring);
                        pRangeSpring->Enable();
                        pRangeSpring->SetParameter(FCSPRM_SPRINGSTIFFNESS,200);
                }
                else
                        pRangeSpring->Disable();
        }
}
```

APPENDIX C

DETAILED PERFORMANCE DATA FOR PILOT STROKE SUBEJCTS

The following table lists the kinematic changes from 4 pilot subjects.

Simulation	Measurement	S1			S2			S3			S4			Group Mean (SD)		
		Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre Test	Post Test	%
Reach & Touch	Duration (s)	3.70	2.56	31	4.82	3.15	35	2.77	1.56	44	2.43	1.59	35	3.43 (1.07)	2.22 (0.78)	36.2 (5.5)
	Smoothness	1020	349	66	1295	646	50	321	312	3	212	79	63	712 (528)	346 (233)	45.5 (29.17)
Cup Placing	Duration (s)	16.06	6.93	57	10.40	5.28	49	3.85	2.48	36	3.94	2.91	26	8.56 (5.86)	4.40 (2.09)	41.95 (13.73)
	Smoothness	79911	7493	91	8322	1313	84	669	455	32	1458	401	72	22590 (38368)	2415 (3411)	69.83 26.32
Catching Falling Objects	Active Force (N)	2.5	4.6	83	7.9	15.4	95	3.4	4.0	17	4.5	5.5	22	4.6 (2.4)	7.4 (5.4)	54.7 (40.43)

APPENDIX D

WOLF MOTOR FUNCTION SUBTESTS

The following table lists the Wolf Motor Function pre and post training test scores for 4 pilot subjects.

Subject	S1			S2			S3			S4		
	Pre	Post	%	Pre	Post	%	Pre	Post	%	Pre	Post	%
Forearm to table side	0.97	0.99	-2	0.98	0.83	15	0.69	0.5	28	0.7	0.47	33
Forearm to box	1.31	1.01	23	1.03	0.91	12	0.79	0.5	37	0.89	0.5	44
Extend elbow side	0.5	0.64	-28	0.68	0.7	-3	0.51	0.57	-12	0.85	0.49	42
Extend elbow side weight	0.65	0.47	28	0.58	0.42	28	0.29	0.19	34	0.87	0.29	67
Hand to table front	0.34	0.34	0	0.56	0.57	-2	0.67	0.32	52	0.78	0.69	12
Hand to box front	0.39	0.86	-121	0.87	0.29	67	0.67	0.37	45	0.92	0.81	12
Reach and retrieve	3.19	2.37	26	5.13	2.35	54	1.13	1.2	-6	1.24	1.03	17
Lift can	4.44	3.67	17	5.27	4.07	23	1.72	1.6	7	2.56	2	22
Lift pencil	3.53	2.56	27	2.16	2.96	-37	2.98	2.65	11	2.79	2.18	22
Lift paper clip	5.5	2.98	46	2.57	1.9	26	2.89	2.75	5	3.66	1.69	54
Stack checkers	9	120	-1233	86.86	45	48	18.52	7.08	62	7.49	9.25	-23
Flip cards	18.17	23.64	-30	10.97	8.08	26	10.48	12.81	-22	8.09	10.3	-27
Turn key	6.09	6.7	-10	3.41	3.69	-8	4.7	4.59	2	4.9	5.16	-5
Fold towel	120	17.34	86	21.28	13.16	38	18.59	20.94	-13	15.6	12.53	20
Lift basket	5.53	4.38	21	4.08	3.03	26	2.22	2.41	-9	3.05	3.12	-2
Sum times	179.6	187.95	-5	146.43	87.96	40	66.85	58.48	13	54.39	50.51	7

APPENDIX E

REACH TO GRASP COMPLETE STATISTICS

Appendix E includes all statistics from ReachtoGrasp test.

E.1 Time After Peak Velocity

ANOVA Table for ATAPVonset2
Row exclusion: HASHATall.svd

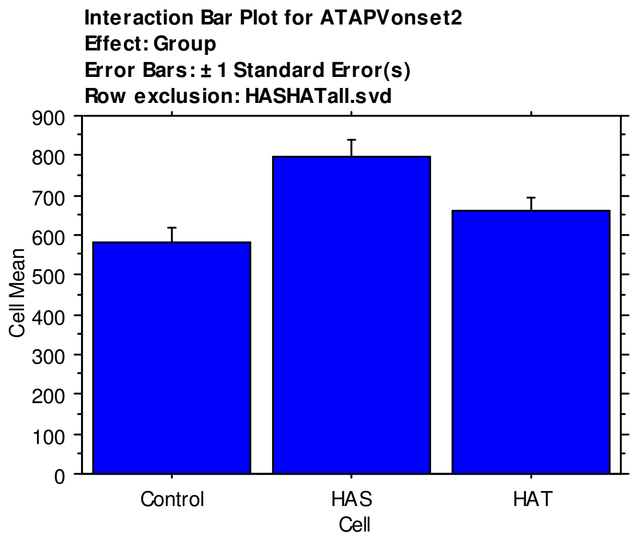
	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	1978640.239	989320.119	1.324	.2848	2.648	.249
Subject(Group)	24	17931782.393	747157.600				
Object	3	391085.173	130361.724	4.894	.0038	14.683	.904
Object * Group	6	261210.236	43535.039	1.634	.1501	9.807	.585
Object * Subject(Group)	72	1917793.353	26636.019				
test	1	283053.044	283053.044	3.740	.0650	3.740	.446
test * Group	2	376571.995	188285.998	2.488	.1043	4.975	.440
test * Subject(Group)	24	1816552.369	75689.682				
Object * test	3	11601.192	3867.064	.289	.8332	.867	.102
Object * test * Group	6	63072.946	10512.158	.786	.5839	4.715	.287
Object * test * Subject(Group)	72	963240.928	13378.346				

Means Table for ATAPVonset2
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	549.510	334.990	35.710
HAS	96	796.669	379.177	38.700
HAT	72	692.864	225.336	26.556

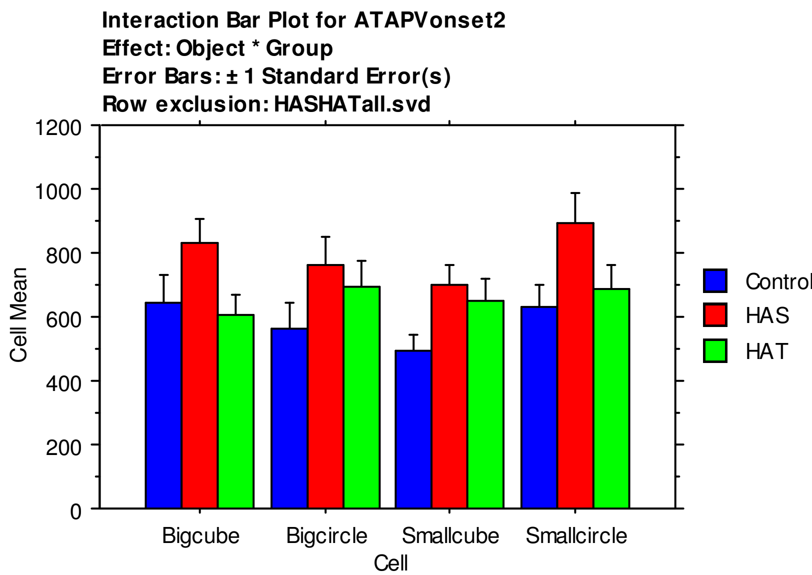
Means Table for ATAPVonset2
Effect: test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	580.686	319.694	48.196
Control, post	44	518.334	350.505	52.841
HAS, pre	48	858.020	401.202	57.909
HAS, post	48	735.318	349.225	50.406
HAT, pre	36	689.190	209.647	34.941
HAT, post	36	696.538	242.949	40.492

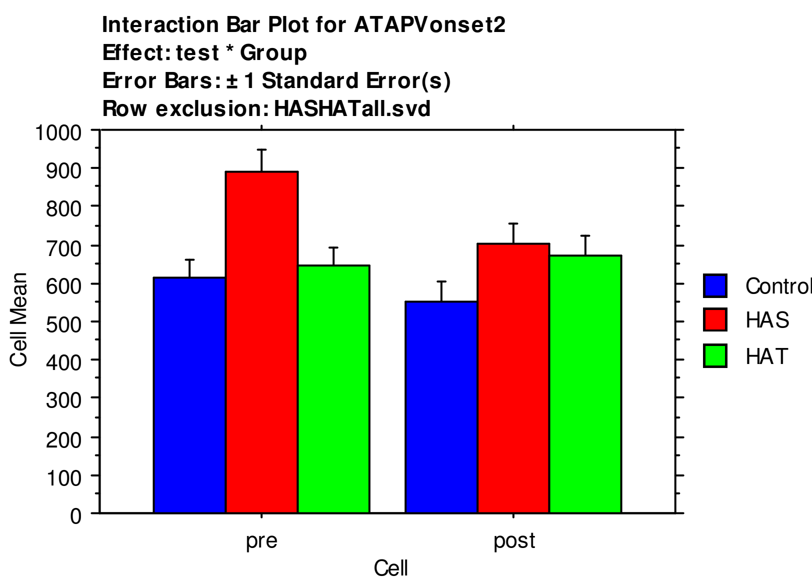


Means Table for ATAPVonset2
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	10	676.300	396.121	125.265
Control, Bigcube, post	10	613.054	422.030	133.458
Control, Bigcircle, pre	10	606.156	369.644	116.892
Control, Bigcircle, post	10	517.867	367.165	116.108
Control, Smallcube, pre	10	526.336	251.404	79.501
Control, Smallcube, post	10	457.239	248.025	78.432
Control, Smallcircle, pre	10	643.283	256.437	81.092
Control, Smallcircle, post	10	613.111	377.452	119.361
HAS, Bigcube, pre	11	918.146	413.855	124.782
HAS, Bigcube, post	11	741.063	314.496	94.824
HAS, Bigcircle, pre	11	866.972	440.990	132.964
HAS, Bigcircle, post	11	660.371	370.986	111.856
HAS, Smallcube, pre	11	783.510	322.341	97.189
HAS, Smallcube, post	11	612.636	273.407	82.435
HAS, Smallcircle, pre	11	990.834	448.344	135.181
HAS, Smallcircle, post	11	798.831	410.434	123.751
HAT, Bigcube, pre	6	591.179	232.130	94.767
HAT, Bigcube, post	6	621.222	213.918	87.332
HAT, Bigcircle, pre	6	641.931	142.909	58.342
HAT, Bigcircle, post	6	747.046	382.485	156.149
HAT, Smallcube, pre	6	630.951	216.489	88.381
HAT, Smallcube, post	6	673.952	246.388	100.587
HAT, Smallcircle, pre	6	727.056	328.258	134.011
HAT, Smallcircle, post	6	646.426	228.930	93.460



Interaction Bar Plot for ATAPVonset2
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
0
200
400
600
800
1000
1200
Bigcube
Bigcircle
Smallcube
Smallcircle
Cell
Control
HAS
HAT



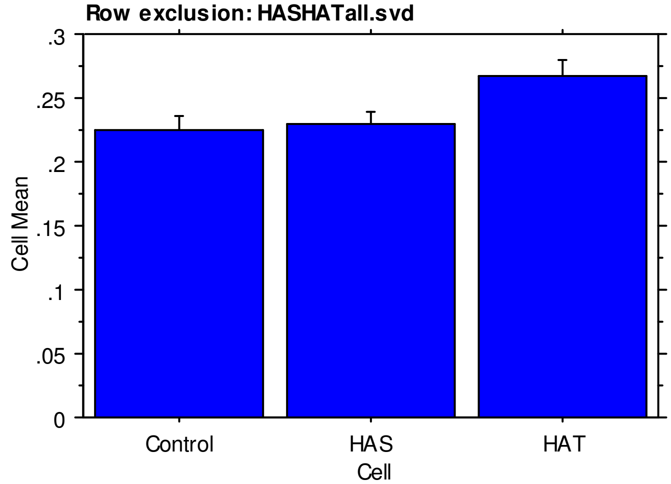
Interaction Bar Plot for ATAPVonset2
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
0
100
200
300
400
500
600
700
800
900
1000
pre
post
Cell
Control
HAS
HAT

E.2 Percentile Time to Peak Deceleration

ANOVA Table for ApercTTD
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	.062	.031	1.428	.2595	2.855	.266
Subject(Group)	24	.524	.022				
Object	3	.023	.008	1.027	.3859	3.080	.260
Object * Group	6	.014	.002	.327	.9209	1.960	.134
Object * Subject(Group)	72	.527	.007				
test	1	3.868E-4	3.868E-4	.022	.8842	.022	.052
test * Group	2	.054	.027	1.502	.2430	3.003	.279
test * Subject(Group)	24	.429	.018				
Object * test	3	.019	.006	1.386	.2540	4.158	.344
Object * test * Group	6	.024	.004	.864	.5255	5.185	.315
Object * test * Subject(Group)	72	.337	.005				

Interaction Bar Plot for ApercTTD
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Means Table for ApercTTD
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	.230	.096	.010
HAS	96	.231	.100	.010
HAT	80	.256	.105	.012

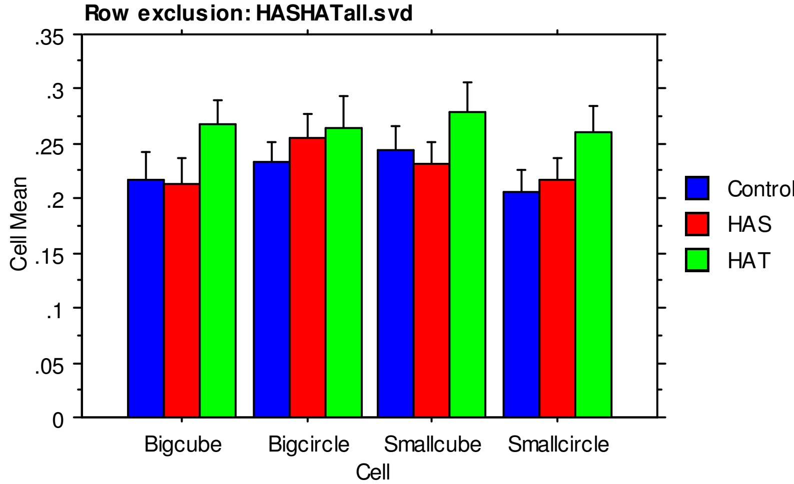
Means Table for ApercTTD
Effect: test * Group
Row exclusion: HASHATall.svd

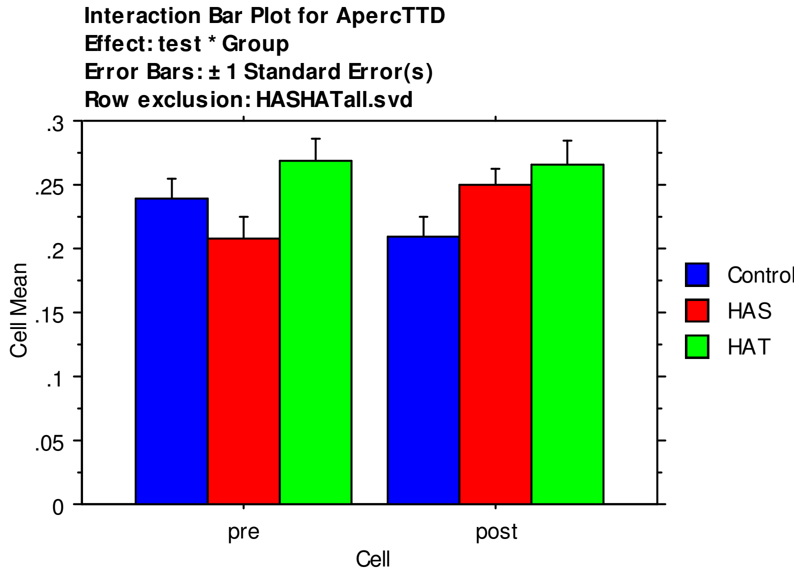
	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	.240	.094	.014
Control, post	44	.220	.099	.015
HAS, pre	48	.217	.110	.016
HAS, post	48	.246	.086	.012
HAT, pre	40	.248	.112	.018
HAT, post	40	.264	.098	.015

Means Table for AprecTTD
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	10	.253	.105	.033
Control, Bigcube, post	10	.182	.104	.033
Control, Bigcircle, pre	10	.222	.102	.032
Control, Bigcircle, post	10	.244	.071	.022
Control, Smallcube, pre	10	.257	.101	.032
Control, Smallcube, post	10	.230	.110	.035
Control, Smallcircle, pre	10	.226	.095	.030
Control, Smallcircle, post	10	.184	.099	.031
HAS, Bigcube, pre	11	.193	.137	.041
HAS, Bigcube, post	11	.234	.065	.020
HAS, Bigcircle, pre	11	.231	.097	.029
HAS, Bigcircle, post	11	.280	.096	.029
HAS, Smallcube, pre	11	.188	.083	.025
HAS, Smallcube, post	11	.273	.088	.027
HAS, Smallcircle, pre	11	.221	.102	.031
HAS, Smallcircle, post	11	.211	.096	.029
HAT, Bigcube, pre	6	.262	.048	.019
HAT, Bigcube, post	6	.274	.102	.042
HAT, Bigcircle, pre	6	.259	.116	.047
HAT, Bigcircle, post	6	.268	.102	.041
HAT, Smallcube, pre	6	.285	.099	.040
HAT, Smallcube, post	6	.272	.095	.039
HAT, Smallcircle, pre	6	.272	.083	.034
HAT, Smallcircle, post	6	.249	.086	.035

Interaction Bar Plot for AprecTTD
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd




Interaction Bar Plot for ApercTTD
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
.3
.25
.2
.15
.1
.05
0
pre
post
Cell
Control
HAS
HAT

E.3 Arm Reaction Time

ANOVA Table for ART
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	546996.513	273498.257	2.286	.1233	4.573	.408
Subject(Group)	24	2870751.712	119614.655				
Object	3	74882.799	24960.933	4.349	.0071	13.047	.860
Object * Group	6	96903.967	16150.661	2.814	.0162	16.883	.861
Object * Subject(Group)	72	413250.916	5739.596				
test	1	45872.111	45872.111	.564	.4598	.564	.108
test * Group	2	92251.940	46125.970	.568	.5743	1.135	.130
test * Subject(Group)	24	1950364.361	81265.182				
Object * test	3	14214.286	4738.095	1.052	.3749	3.156	.266
Object * test * Group	6	23056.342	3842.724	.853	.5334	5.120	.311
Object * test * Subject(Group)	72	324245.655	4503.412				

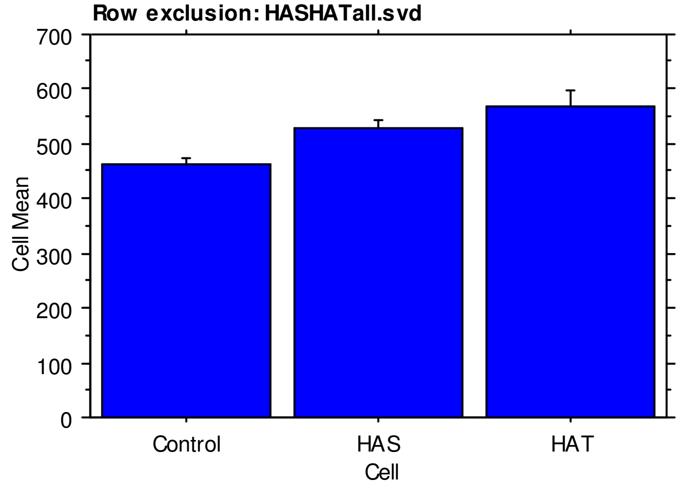
Means Table for ART
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	464.837	99.423	10.599
HAS	96	530.156	122.077	12.459
HAT	72	569.473	254.420	29.984

Means Table for ART
Effect: test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	483.140	90.720	13.677
Control, post	44	446.534	105.280	15.872
HAS, pre	48	564.590	116.307	16.788
HAS, post	48	495.722	119.052	17.184
HAT, pre	36	556.734	170.148	28.358
HAT, post	36	582.213	319.413	53.235

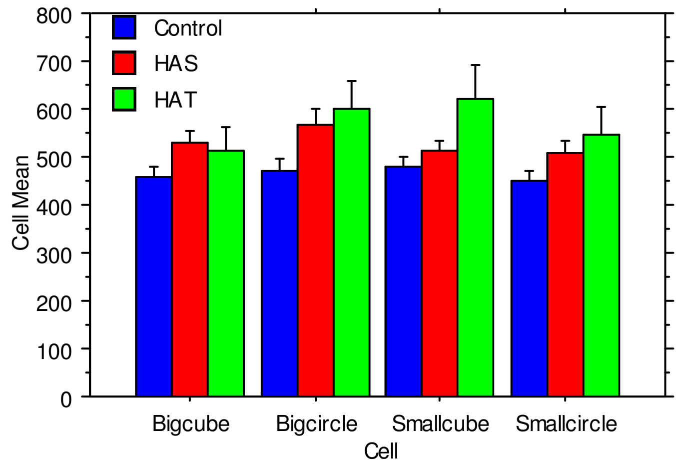
Interaction Bar Plot for ART
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



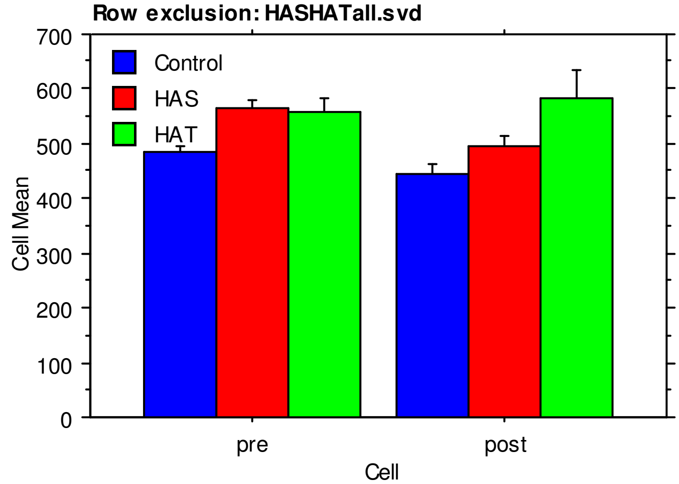
Means Table for ART
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	11	477.286	95.289	28.731
Control, Bigcube, post	11	436.319	98.400	29.669
Control, Bigcircle, pre	11	488.182	109.349	32.970
Control, Bigcircle, post	11	454.212	120.574	36.354
Control, Smallcube, pre	11	482.659	91.210	27.501
Control, Smallcube, post	11	478.232	114.719	34.589
Control, Smallcircle, pre	11	484.432	77.237	23.288
Control, Smallcircle, post	11	417.373	89.775	27.068
HAS, Bigcube, pre	12	570.225	100.715	29.074
HAS, Bigcube, post	12	491.155	129.623	37.419
HAS, Bigcircle, pre	12	605.570	166.807	48.153
HAS, Bigcircle, post	12	530.387	122.830	35.458
HAS, Smallcube, pre	12	549.815	94.218	27.198
HAS, Smallcube, post	12	474.278	109.411	31.584
HAS, Smallcircle, pre	12	532.752	87.995	25.402
HAS, Smallcircle, post	12	487.069	121.581	35.097
HAT, Bigcube, pre	9	510.695	135.278	45.093
HAT, Bigcube, post	9	515.809	258.482	86.161
HAT, Bigcircle, pre	9	615.182	182.639	60.880
HAT, Bigcircle, post	9	585.765	306.463	102.154
HAT, Smallcube, pre	9	581.114	199.868	66.623
HAT, Smallcube, post	9	659.375	394.596	131.532
HAT, Smallcircle, pre	9	519.943	163.199	54.400
HAT, Smallcircle, post	9	567.904	343.533	114.511

Interaction Bar Plot for ART
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Interaction Bar Plot for ART
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



E.4 Hand Maximum Aperture Time

ANOVA Table for HAperRT
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	21899.500	10949.750	.090	.9141	.180	.062
Subject(Group)	24	2916750.315	121531.263				
Object	3	326485.867	108828.622	4.956	.0035	14.867	.908
Object * Group	6	34361.525	5726.921	.261	.9533	1.565	.115
Object * Subject(Group)	72	1581170.545	21960.702				
test	1	265762.268	265762.268	4.890	.0368	4.890	.557
test * Group	2	30263.377	15131.688	.278	.7594	.557	.088
test * Subject(Group)	24	1304416.046	54350.669				
Object * test	3	23482.284	7827.428	.675	.5701	2.025	.182
Object * test * Group	6	105631.424	17605.237	1.519	.1844	9.111	.547
Object * test * Subject(Group)	72	834737.532	11593.577				

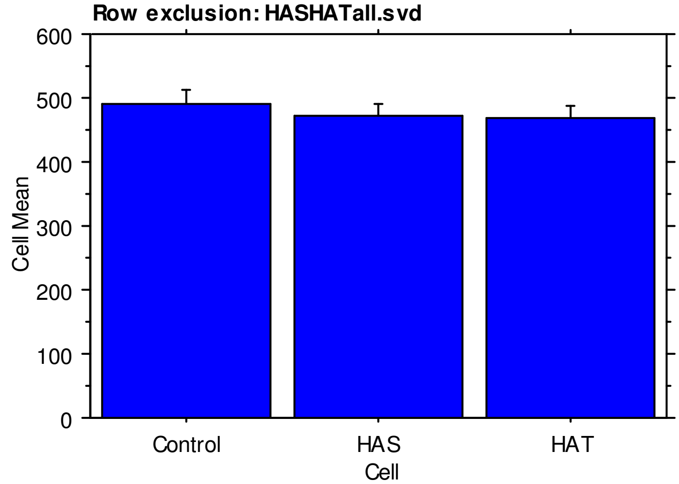
Means Table for HAperRT
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	491.198	213.442	22.753
HAS	96	473.293	166.767	17.021
HAT	80	467.355	192.253	21.495

Means Table for HAperRT
Effect: test * Group
Row exclusion: HASHATall.svd

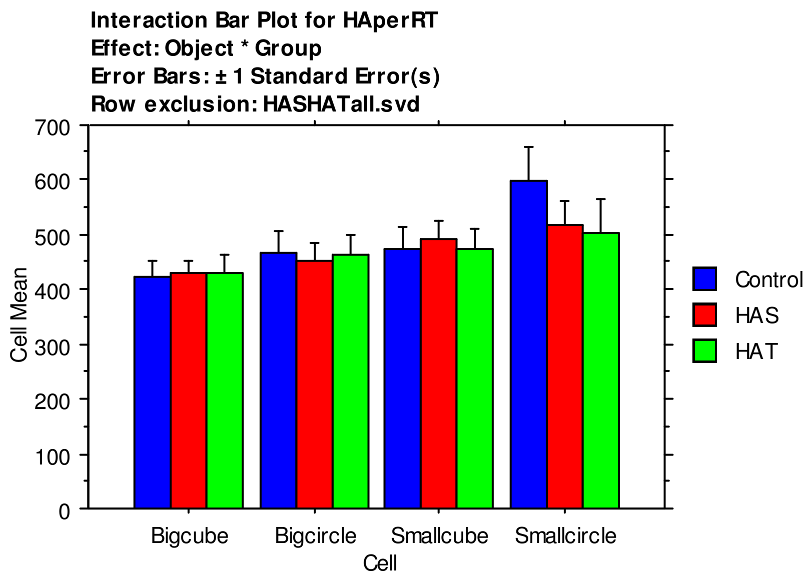
	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	519.086	212.194	31.989
Control, post	44	463.309	213.441	32.177
HAS, pre	48	492.771	143.137	20.660
HAS, post	48	453.816	186.952	26.984
HAT, pre	40	504.233	220.947	34.935
HAT, post	40	430.477	152.522	24.116

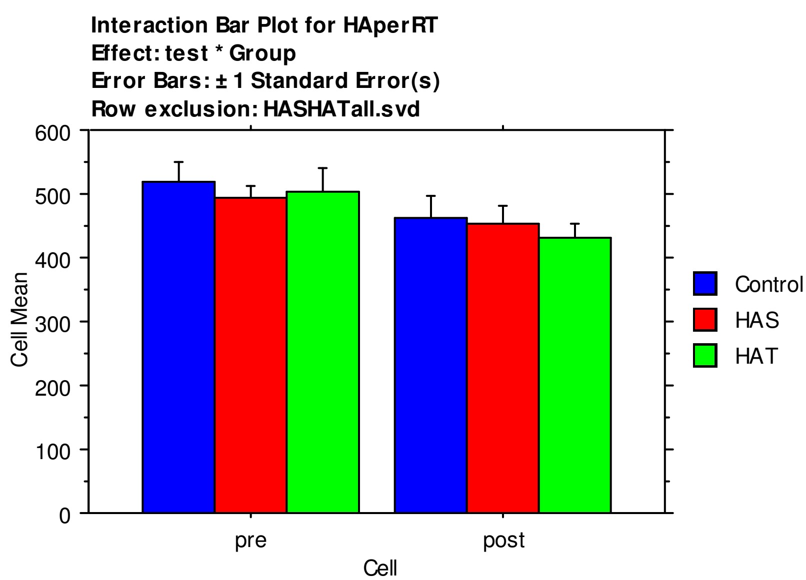
Interaction Bar Plot for HAperRT
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Means Table for HAperRT
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	11	461.717	157.167	47.388
Control, Bigcube, post	11	386.315	100.427	30.280
Control, Bigcircle, pre	11	483.970	134.348	40.508
Control, Bigcircle, post	11	450.556	224.965	67.829
Control, Smallcube, pre	11	488.414	186.885	56.348
Control, Smallcube, post	11	460.096	203.805	61.450
Control, Smallcircle, pre	11	642.242	305.352	92.067
Control, Smallcircle, post	11	556.271	278.291	83.908
HAS, Bigcube, pre	12	451.014	109.846	31.710
HAS, Bigcube, post	12	410.266	82.760	23.891
HAS, Bigcircle, pre	12	487.892	186.456	53.825
HAS, Bigcircle, post	12	417.875	115.797	33.428
HAS, Smallcube, pre	12	525.498	161.105	46.507
HAS, Smallcube, post	12	460.704	155.793	44.973
HAS, Smallcircle, pre	12	506.680	106.989	30.885
HAS, Smallcircle, post	12	526.419	309.072	89.222
HAT, Bigcube, pre	10	449.819	168.463	53.273
HAT, Bigcube, post	10	410.331	129.658	41.001
HAT, Bigcircle, pre	10	508.353	193.793	61.283
HAT, Bigcircle, post	10	415.756	132.935	42.038
HAT, Smallcube, pre	10	500.369	139.020	43.962
HAT, Smallcube, post	10	447.411	197.996	62.612
HAT, Smallcircle, pre	10	558.389	345.971	109.406
HAT, Smallcircle, post	10	448.410	160.478	50.748


Interaction Bar Plot for HAperRT
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
0
100
200
300
400
500
600
700
Bigcube
Bigcircle
Smallcube
Smallcircle
Cell
Control
HAS
HAT


Interaction Bar Plot for HAperRT
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
0
100
200
300
400
500
600
pre
post
Cell
Control
HAS
HAT

E. 5 Hand Maximum Aperture

ANOVA Table for HPAper
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	1.843	.921	2.997	.0689	5.993	.519
Subject(Group)	24	7.380	.307				
Object	3	.896	.299	36.699	<.0001	110.096	1.000
Object * Group	6	.094	.016	1.929	.0877	11.572	.673
Object * Subject(Group)	72	.586	.008				
test	1	.023	.023	.405	.5303	.405	.092
test * Group	2	.063	.031	.553	.5825	1.105	.128
test * Subject(Group)	24	1.360	.057				
Object * test	3	.017	.006	2.387	.0760	7.161	.567
Object * test * Group	6	.017	.003	1.164	.3352	6.983	.424
Object * test * Subject(Group)	72	.172	.002				

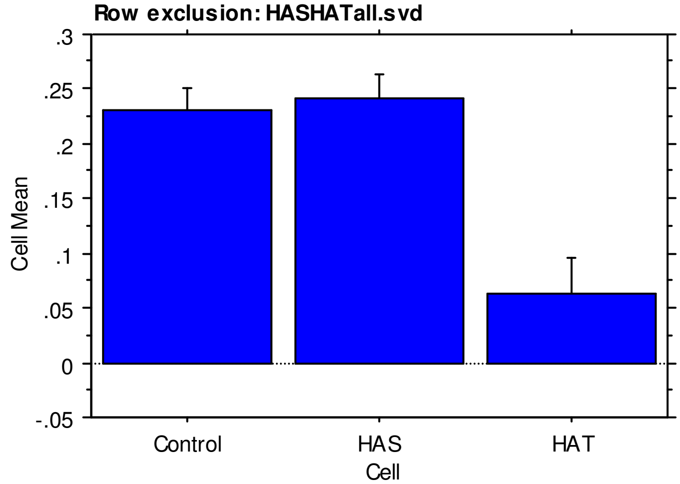
Means Table for HPAper
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	.231	.191	.020
HAS	96	.242	.216	.022
HAT	80	.063	.285	.032

Means Table for HPAper
Effect: test * Group
Row exclusion: HASHATall.svd

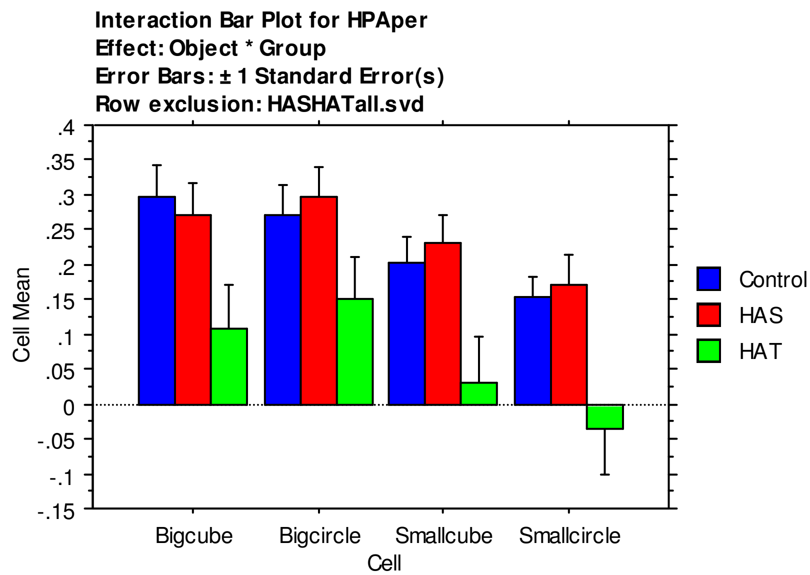
	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	.251	.189	.028
Control, post	44	.210	.194	.029
HAS, pre	48	.254	.226	.033
HAS, post	48	.230	.207	.030
HAT, pre	40	.063	.351	.056
HAT, post	40	.063	.203	.032

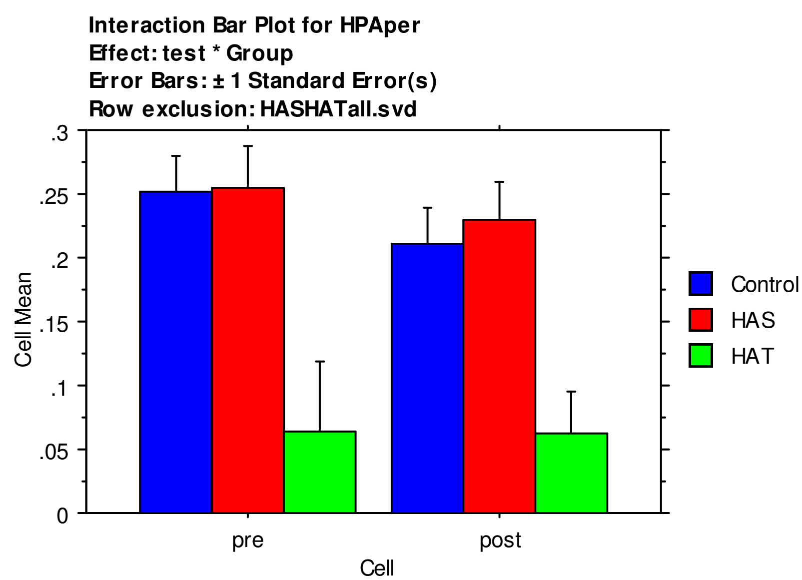
Interaction Bar Plot for HPAper
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Means Table for HPAper
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	11	.331	.207	.062
Control, Bigcube, post	11	.264	.220	.066
Control, Bigcircle, pre	11	.288	.187	.056
Control, Bigcircle, post	11	.253	.235	.071
Control, Smallcube, pre	11	.229	.199	.060
Control, Smallcube, post	11	.174	.160	.048
Control, Smallcircle, pre	11	.158	.130	.039
Control, Smallcircle, post	11	.150	.146	.044
HAS, Bigcube, pre	12	.284	.248	.072
HAS, Bigcube, post	12	.255	.218	.063
HAS, Bigcircle, pre	12	.327	.220	.063
HAS, Bigcircle, post	12	.266	.223	.064
HAS, Smallcube, pre	12	.238	.196	.056
HAS, Smallcube, post	12	.222	.208	.060
HAS, Smallcircle, pre	12	.168	.236	.068
HAS, Smallcircle, post	12	.175	.191	.055
HAT, Bigcube, pre	10	.127	.332	.105
HAT, Bigcube, post	10	.091	.209	.066
HAT, Bigcircle, pre	10	.150	.340	.107
HAT, Bigcircle, post	10	.150	.202	.064
HAT, Smallcube, pre	10	.014	.374	.118
HAT, Smallcube, post	10	.046	.190	.060
HAT, Smallcircle, pre	10	-.038	.377	.119
HAT, Smallcircle, post	10	-.035	.195	.062


Interaction Bar Plot for HPAper
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
.4
.35
.3
.25
.2
.15
.1
.05
0
-.05
-.1
-.15
Bigcube
Bigcircle
Smallcube
Smallcircle
Cell
Control
HAS
HAT


Interaction Bar Plot for HPAper
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
Cell Mean
.3
.25
.2
.15
.1
.05
0
pre
post
Cell
Control
HAS
HAT

E. 6 Time to Hand Maximum Aperture

ANOVA Table for HTTPAPer
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	4521569.945	2260784.972	3.972	.0323	7.944	.653
Subject(Group)	24	13660031.580	569167.982				
Object	3	1559464.370	519821.457	9.992	<.0001	29.975	.999
Object * Group	6	209778.478	34963.080	.672	.6725	4.032	.247
Object * Subject(Group)	72	3745861.928	52025.860				
test	1	1583.088	1583.088	.013	.9093	.013	.051
test * Group	2	628914.690	314457.345	2.635	.0923	5.270	.464
test * Subject(Group)	24	2863874.772	119328.115				
Object * test	3	210337.787	70112.596	2.570	.0609	7.709	.604
Object * test * Group	6	236559.859	39426.643	1.445	.2096	8.670	.522
Object * test * Subject(Group)	72	1964503.346	27284.769				

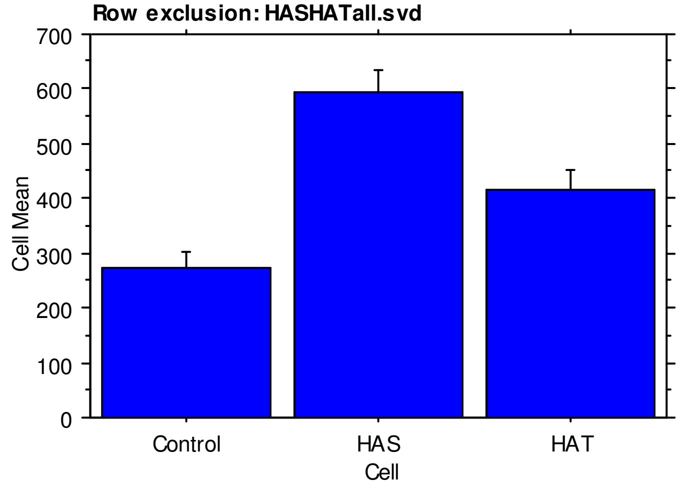
Means Table for HTTPAPer
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	274.567	269.060	28.682
HAS	96	595.606	385.776	39.373
HAT	80	417.401	314.290	35.139

Means Table for HTTPAPer
Effect: test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	263.273	224.234	33.805
Control, post	44	285.861	309.723	46.692
HAS, pre	48	670.809	443.263	63.980
HAS, post	48	520.404	304.596	43.965
HAT, pre	40	395.638	256.683	40.585
HAT, post	40	439.163	365.009	57.713

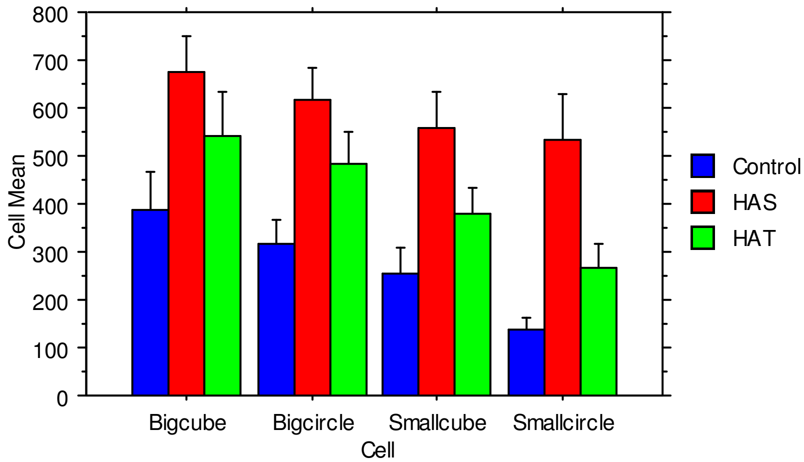
Interaction Bar Plot for HTTPAPer
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



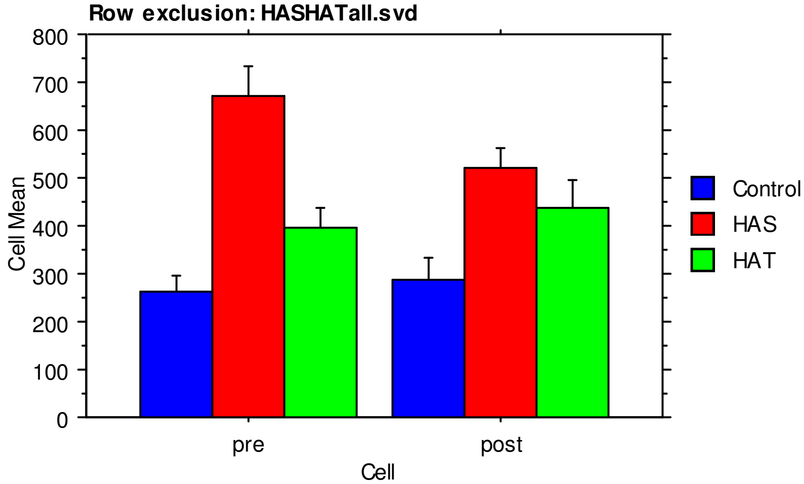
Means Table for HTTPAPer
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	11	378.030	312.439	94.204
Control, Bigcube, post	11	397.506	434.621	131.043
Control, Bigcircle, pre	11	290.677	154.192	46.491
Control, Bigcircle, post	11	345.929	303.335	91.459
Control, Smallcube, pre	11	247.215	222.109	66.968
Control, Smallcube, post	11	264.093	263.977	79.592
Control, Smallcircle, pre	11	137.172	111.331	33.568
Control, Smallcircle, post	11	135.915	137.720	41.524
HAS, Bigcube, pre	12	783.514	402.833	116.288
HAS, Bigcube, post	12	568.347	300.842	86.846
HAS, Bigcircle, pre	12	640.851	381.572	110.150
HAS, Bigcircle, post	12	588.975	278.115	80.285
HAS, Smallcube, pre	12	661.919	454.238	131.127
HAS, Smallcube, post	12	450.731	265.972	76.780
HAS, Smallcircle, pre	12	596.951	551.760	159.279
HAS, Smallcircle, post	12	473.563	377.488	108.972
HAT, Bigcube, pre	10	451.028	232.469	73.513
HAT, Bigcube, post	10	631.783	524.854	165.973
HAT, Bigcircle, pre	10	426.808	295.258	93.369
HAT, Bigcircle, post	10	536.278	307.514	97.244
HAT, Smallcube, pre	10	402.994	242.877	76.805
HAT, Smallcube, post	10	352.844	271.326	85.801
HAT, Smallcircle, pre	10	301.721	266.365	84.232
HAT, Smallcircle, post	10	235.747	166.507	52.654

Interaction Bar Plot for HTTPAPer
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Interaction Bar Plot for HTTPAPer
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



E.7 Time to Peak Velocity overlap with Time to Maximum Aperture

ANOVA Table for TTPV-TTPAper
Row exclusion: HASHATall.svd

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
Group	2	3123851.794	1561925.897	2.705	.0872	5.410	.475
Subject(Group)	24	13858211.209	577425.467				
Object	3	1506752.179	502250.726	9.217	<.0001	27.650	.998
Object * Group	6	187928.892	31321.482	.575	.7492	3.449	.213
Object * Subject(Group)	72	3923558.395	54493.867				
test	1	86983.471	86983.471	.522	.4768	.522	.104
test * Group	2	669491.884	334745.942	2.011	.1558	4.022	.363
test * Subject(Group)	24	3995425.545	166476.064				
Object * test	3	187499.121	62499.707	2.039	.1160	6.117	.493
Object * test * Group	6	223939.209	37323.202	1.218	.3073	7.306	.443
Object * test * Subject(Group)	72	2206862.752	30650.872				

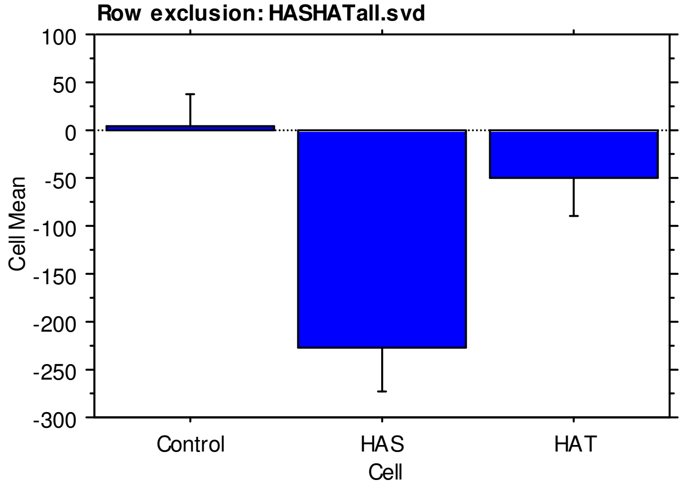
Means Table for TTDecc-PAPer
Effect: Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control	88	3.849	309.306	32.972
HAS	96	-228.026	441.386	45.049
HAT	80	-49.230	366.387	40.963

Means Table for TTDecc-PAPer
Effect: test * Group
Row exclusion: HASHATall.svd

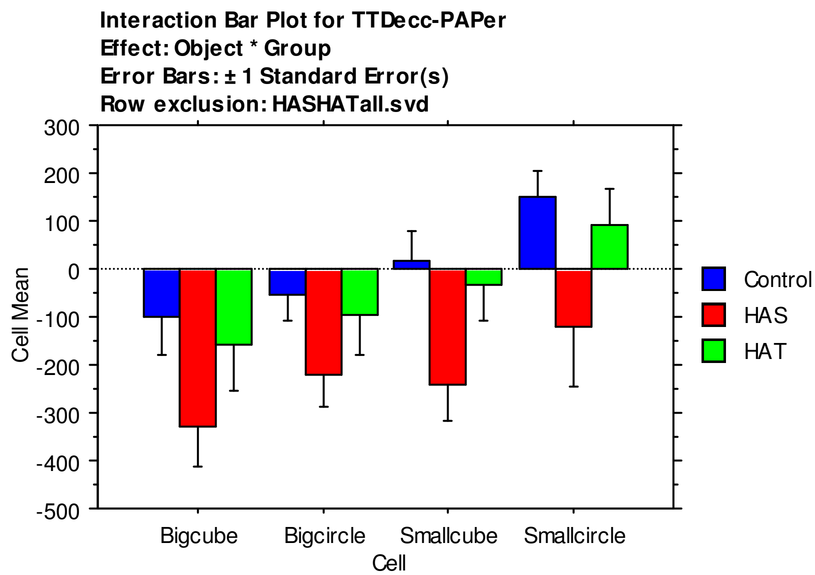
	Count	Mean	Std. Dev.	Std. Err.
Control, pre	44	51.780	256.705	38.700
Control, post	44	-44.083	350.665	52.865
HAS, pre	48	-282.703	526.155	75.944
HAS, post	48	-173.350	332.930	48.054
HAT, pre	40	-20.789	385.048	60.881
HAT, post	40	-77.672	349.285	55.227

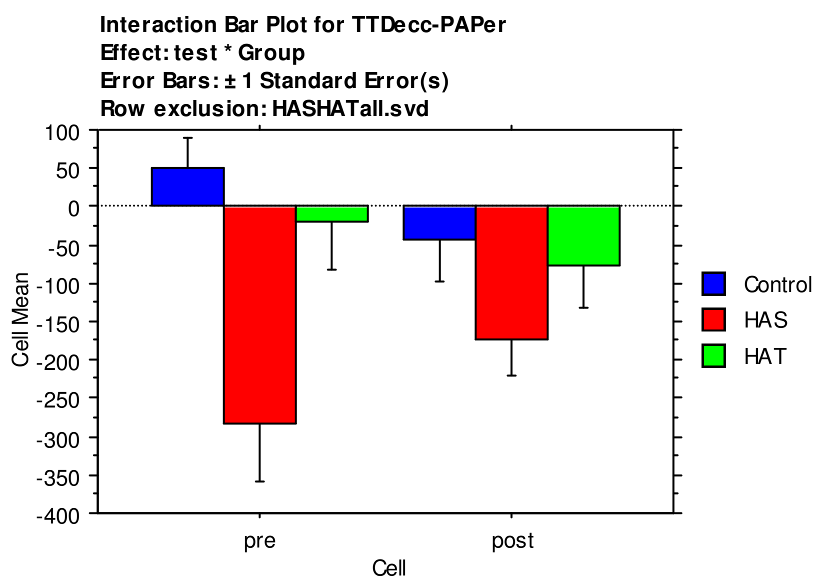
Interaction Bar Plot for TTDecc-PAPer
Effect: Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd



Means Table for TTDecc-PAPer
Effect: Object * test * Group
Row exclusion: HASHATall.svd

	Count	Mean	Std. Dev.	Std. Err.
Control, Bigcube, pre	11	-27.636	311.843	94.024
Control, Bigcube, post	11	-169.948	440.674	132.868
Control, Bigcircle, pre	11	-15.959	196.347	59.201
Control, Bigcircle, post	11	-88.879	327.286	98.680
Control, Smallcube, pre	11	50.263	252.228	76.050
Control, Smallcube, post	11	-20.550	341.740	103.039
Control, Smallcircle, pre	11	200.455	218.264	65.809
Control, Smallcircle, post	11	103.047	258.078	77.813
HAS, Bigcube, pre	12	-451.027	415.634	119.983
HAS, Bigcube, post	12	-209.973	354.783	102.417
HAS, Bigcircle, pre	12	-228.121	352.429	101.738
HAS, Bigcircle, post	12	-209.468	344.505	99.450
HAS, Smallcube, pre	12	-361.935	416.973	120.370
HAS, Smallcube, post	12	-123.352	275.551	79.545
HAS, Smallcircle, pre	12	-89.728	793.979	229.202
HAS, Smallcircle, post	12	-150.608	383.327	110.657
HAT, Bigcube, pre	10	-69.988	350.629	110.879
HAT, Bigcube, post	10	-248.731	472.120	149.298
HAT, Bigcircle, pre	10	-46.486	457.132	144.558
HAT, Bigcircle, post	10	-146.633	274.463	86.793
HAT, Smallcube, pre	10	-42.943	360.823	114.102
HAT, Smallcube, post	10	-25.911	315.593	99.799
HAT, Smallcircle, pre	10	76.263	407.346	128.814
HAT, Smallcircle, post	10	110.586	225.143	71.196


Interaction Bar Plot for TTDecc-PAPer
Effect: Object * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
300
200
100
0
-100
-200
-300
-400
-500
Cell Mean
Bigcube
Bigcircle
Smallcube
Smallcircle
Cell
Control
HAS
HAT


Interaction Bar Plot for TTDecc-PAPer
Effect: test * Group
Error Bars: ± 1 Standard Error(s)
Row exclusion: HASHATall.svd
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
Cell Mean
pre
post
Cell
Control
HAS
HAT

APPENDIX F

MELBOURNE SCORES

The following table lists the Melbourne score and three sub-test score from all 13 subjects.

	MAUULF (%)			Forward reach (s)			Reach sideway (s)			Hand to mouth (s)			Composite Time(s)		
	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
RAVR1	40.2	42.6	2.4	1.9	1.2	-0.7	U	1.4	na	U	U	na	1.9	1.2	-0.7
RAVR2	74.6	75.4	0.8	3.6	2.9	-0.7	3.7	2.3	-1.4	15.1	10.7	-4.4	22.4	15.9	-6.5
RAVR3	59.8	67.2	7.6	2.9	2.1	-1.4	2.2	0.8	-1.4	5.4	4.6	-0.8	10.5	6.9	-3.6
RAVR4	76.2	77.1	0.9	4.5	1.5	-3.0	2.4	1.8	-0.6	2.2	1.6	-0.6	9.1	4.9	-4.2
RAVR5	68.2	78.6	10.4	1.2	0.5	-0.7	1.3	0.5	-0.8	7.3	2.9	-4.4	9.8	3.8	-6.0
RAVR6	49	51	2	3.2	2.9	-0.3	2.7	2.2	-0.5	1.1	2.5	1.4	6.96	7.57	0.61
RAVR7	66.3	76	9.7	0.8	0.4	-0.4	1.3	0.4	-0.7	1.4	0.5	-0.9	3.58	1.39	-2.19
RAVR8	67	74	7	0.8	0.7	-0.1	0.9	0.5	-0.4	1.0	0.8	-0.2	2.72	2.04	-0.68
RAVR9	70.1	85	14.9	1.0	0.7	-0.3	0.6	0.6	0	0.7	0.6	-0.1	2.33	1.93	-0.4
MeanRAVR	63.5	69.7	6.2	2.2	1.4	-0.8	1.9	1.2	-0.7	4.3	3.0	-1.3	7.7	5.1	-2.6
Combine1	53.4	50.8	-2.6	2.0	1.8	-0.2	1.7	1.8	0.1	4.7	1.7	-3.0	8.4	5.3	-3.1
Combine2	41.8	54.1	12.3	3.2	3.9	0.7	3.6	1.6	-2.0	6.6	1.5	-5.1	13.4	7.0	-6.4
Combine3	52.5	86.9	7.4	1.7	1.2	-0.5	1.7	1.1	-0.6	2.8	1.8	-1.0	6.2	4.1	-2.1
Combine4	79.5	86.9	7.4	1.7	1.2	-0.5	1.7	1.1	-0.6	2.8	1.8	-1.0	6.2	4.1	-2.1
MeanComb	56.8	63.3	6.5	2.5	2.1	-0.4	2.8	1.9	-0.9	4.4	2.6	-1.7	9.7	6.7	-3.0
GrandMean	61.4	67.7	**6.3	2.3	1.6	*-.7	2.2	1.4	**-1	4.3	2.9	*-1.4	8.3	5.6	**-3.7
Grand SD	13.0	14.3	5.2	1.2	0.9	1.0	1.2	0.8	0.6	4.1	2.9	2.3	5.6	4.1	2.4

*p<.05; **p<.001, Diff = Difference

APPENDIX G

CLINICAL MEASUREMENTS FOR CEREBRAL PALSY SUBJECTS

The following table lists clinical measurements results including Active Range of Motion, Grip Dynamometry & Functional Levels of Hemiplegia Measurements.

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Subj.	Shoulder Abd			Shoulder Flex			Elbow Ext			Supination			Wrist Ext			Grip			Pinch			FLH		
	R	P	D	R	P	D	R	P	D	R	P	D	R	P	D	R	P	D	R	P	D	R	P	D
RAVR3	150	150	0	130	145	15	wnl	wnl		75	65	-10	45	55	10	6	14	8	3	7	4	6	7	1
RAVR4	150	155	5	150	145	-5	wnl	wnl		-60	-10	50	60	65	6	3	3	0	3	4	1	4	5	1
RAVR5	96	100	4	94	110	16	wnl	wnl		66	76	10	8	12	4	nt	nt	nt	nt	nt	nt	5	6	1
RAVR6	68	70	2	80	90	10	-74	-66		-65	-45	20												
RAVR7	142	146	4	160	166	6	-15	-5		20	35	15												
RAVR8	94	90	-4	110	126	16				25	32	7												
RAVR9	108	112	4	130	142	12	-15	-15		55	60	5												
Mean			2.1			10						13.9			6			4			3			1
Combine1	135	135	0	135	140	5	wnl	wnl		75	60	-15	0	49	49	5	8	3	3.6	4	0.4	5	5	0
Combine2	110	125	15	105	135	30	-25	-20	5	10	35	25	0	0	0	12	14	2	0	0	0	3	2	1
Combine3	105	160	55	120	135	15	-20	-10	10	45	55	10	0	0	0	4.3	4.6	0.3	2.6	1.6	-1	1	4	3
Combine4	145	150	5	140	135	-5	-20	-15	5	65	70	10	50	50	0	27	35	8	10	11	-1	7	7	0
CombMean			19			11			7			8			12			1			0			1
GrandMean			12			10			7			11			10			*2			1			1
Grand SD			20			13			3			22			18			3			2			1

* p<.001

R: Pre, P: Post, D: Diff

Abd = Abduction, Flex = Flexion, Ext = Extension, FLH = Functional Level of Hemiplegia, Out-Pt = Outpatient / RAVR, Camp = CIMT +RAVR, wnl = within normal limits, nt = not tested, Diff= Difference

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